DEVELOPMENT OF CRITERIA FOR DURABILITY
OF MODIFIED ASPHALTS

BY

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DEVELOPMENT OF CRITERIA FOR DURABILITY OF MODIFIED ASPHALTS

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A laboratory investigation was conducted to evaluate the effects of a few promising modifiers on the temperature susceptibility and long-term aging characteristics of typical asphalt cements and asphalt concrete mixtures used in Florida. The seven types of modifiers evaluated in this study include (1) gilsonite, (2) carbon black, (3) fine ground tire rubber (GTR-80), (4) coarse ground tire rubber (GTR-40), (5) styrene-butadiene rubber (SBR), (6) ethylene vinyl acetate (EVA), (7) styrene-ethylene-butylene-styrene (SEBS). These modifiers were blended with an AC-30, AC-20 and AC-5. These modified and unmodified asphalts were subjected to the thin film oven test (TFOT) to simulate the short-term aging effect that occurs in the hot-mix plant process. Eleven of these modified asphalts were subjected to the thin film oven test (TFOT) and rolling thin film oven test (RTFOT) at higher oven temperatures to simulate the long-term aging effects on these modifiers. All these asphalts and asphalt blends were evaluated by rheological and chemical tests.

The eleven modified asphalt blends and unmodified AC-30 were also used to make Florida type S-1 structural course and type FC-2 friction course mixtures. These mixtures were compacted into Marshall specimens for age-hardening and subsequent testing. These aged and unaged asphalt blend mixtures were evaluated by resilient modulus, indirect tensile strength, and fracture energy tests at two different temperatures. Asphalt residues were recovered from the broken samples and evaluated by consistency tests.

The test results indicate that the modified asphalt mixtures appear to have a more pronounced delayed elastic behavior as compared with that of the unmodified asphalt mixture. The laboratory RTFOT aging process performed at a temperature of 135°C can simulate a one-year field aging effect, while the California tilt oven process for a duration of 168 hours can simulate an eight-year field aging under typical Florida conditions. In addition, the SHRP pressure aging vessel (PAV) at 100°C for a duration of 40 hours could simulate an aging effect of over 8 years of service under typical Florida conditions.

CHAPTER 1
INTRODUCTION

1.1 Background and Research Needs

Asphalt concrete is affected by temperature, it tends to become stiffer at low service temperature and softer at high temperature. Thus an asphalt pavement has a greater tendency to crack in the winter time and to shove and/or rut in the summer time. The service life of asphalt pavements is affected by the resistance to cracking and rutting of the asphalt concrete. A possible alternative to extend the life of asphalt pavements is to use a modified asphalt in the paving mixture [1]. The addition of modifiers to asphalt cements may impart certain desirable characteristics to the asphalt binders, such as lower temperature susceptibility and increased elastic response at high temperature. Because modified asphalt pavements are quite new in the United States, there is still a lot of uncertainties about the long-term performance of these pavements. There are, at present, no widely accepted test procedures and criteria for the selection of these modifiers.

Carbon black and chemical-based light stabilizers are now widely used in asphalt mixtures to provide a stiffer pavement at high service temperature. Polymers are recognized as the most popular modifiers in asphalt mixtures. They are made up of long-chain bonded molecules and include plastics, rubbers, and adhesives. These materials behave like elastic solids under certain conditions and like very viscous liquids under others. The addition of these materials in asphalt mixtures may eliminate or reduce certain pavement distresses, such as rutting, cracking, and stripping.

Modifiers are known to react differently with asphalt cements from different sources. Therefore, the reaction of a modifier when mixed with one asphalt may vary greatly from that when mixed with another asphalt. Specifications for asphalt cements may not be suitable for the asphalt-modifier blends. It is necessary to investigate the appropriate test procedures for evaluation of the modified asphalt binders. Also, the effects of air, ultraviolet light, and elevated temperature on these modified asphalt binders are unknown. Long-term laboratory tests should be conducted to evaluate the long-term performance of these modified asphalt binders and mixtures and also to aid identify the maximum benefits of these new asphalt blends.

1.2 Objectives of the Study

The main objectives of this research are as follows:

1. To study the effect of selected modifiers to the temperature susceptibility and flow properties of typical paving asphalts.

2. To determine the optimum modifier content of selected modifiers for typical paving mixtures used in Florida.
3. To study the aging characteristics of selected modified asphalts.
4. To develop and evaluate the test methods and criteria for selection of modified asphalt to be used in paving mixtures.

CHAPTER 2
LITERATURE REVIEW

2.1 Classification of Modifiers

Modifiers or additives have been added to asphalt cement in an attempt to improve the performance of asphalt paving mixtures. A large number of asphalt modifiers have been introduced into asphalt pavements during the last fifteen years. A definition of asphalt modifiers from Hass et al. [2,3] is as follow.

> An asphalt cement additive is a material which would normally be added to and/or mixed with the asphalt before mix production, or during mix production, to improve the properties and/or performance of the resulting binder and/or the mix, or where an aged binder is involved, as in recycling, to improve or restore the original properties of the aged binder.

Epps [4] stated that an ideal modified asphalt should have 1) higher stiffness at high service temperature, to reduce rutting and shoving; 2) lower stiffness at cold ambient temperatures, to reduce cracking; 3) lower viscosity at processing temperatures, to improve workability; and 4) improved adhesion of asphalt to aggregate in the presence of water and water vapor, to reduce stripping. Similar statements have been reported by Shuler et al. [5], who have studied the useful service life of rubber polymer modified asphalt in the state of Arizona for fifteen years.

A comprehensive investigation of modifiers has been presented by many researchers such as Haas et al.[2,3], Terrel and Walter [6], and Button [7]. A summary of these modifiers is listed in Table 2-1.

2.2. Effects of Modifiers on Asphalt Mixtures

2.2.1 Effects of Gilsonite and Carbon Black

Gilsonite is a pure natural hydrocarbon which was found in the Utah Basin of eastern Utah by Sam Gilson in 1885. It is a natural hard asphalt that has low penetration (0 to 3 at 77°F) and high Ring and Ball softening point (250°F to 350°F) [8], and it is as black as coal and as shiny as crystal. The addition of gilsonite can result in a substantial increase in Marshall stability of the asphalt mixtures and increase in viscosity of the binders at high temperature. However, it generally also results in increased viscosity at low temperature. A paving project using gilsonite was constructed on New Jersey Route 35 in 1987. The rut depth was significantly reduced through the use of gilsonite. Another project conducted in Alabama in 1987 indicated that gilsonite was troublesome to handle since it was supplied in 50-100 pound bags [7].

Carbon black is widely used as a reinforcing agent in rubbers and as a pigment, electrically conductive filler or shield against ultraviolet radiation in plastic. The use of carbon black in rubbers is quite different from that used in

Table 2-1 Classification of Asphalt Modifiers(1,2,3)

Type	Examples
1 Mineral Filler	Carbon black, Baghouse fines, Hydrated lime, Portland cement Fly ash, Silica fume, Sulfur
2 Extender	Sulfur, Lignin
Polymer	
3 Rubber	
a.Natural latex	Natural rubber
b.Synthetic latex	Styrene butadiene rubber (SBR)
c.Block copolymer	Styrene butadiene styrene (SBS)
d.Reclaimed rubber	Crumb tire rubber
4.Plastic	Polyethylene (PE) Polypropylene (PP) Ethylene vinyl acetate (EVA) Polyvinyl Chloride (PVC)
5.Combination	Blends of polymers in 3 &4
6.Fiber	Natural: Rock wool Man-Made Polypropylene Polyester Fiberglass
7.Oxidant	Manganese salts
8.Antioxidant	Lead compounds Carbon black Hydrated lime Phenols Diethyldithio carbamates
9 Hydrocarbons	Tall oil, Aromatics, Naphthenics Paraffinics/Wax, Vacuum gas oil Petroleum/Plastic Resins Asphaltenes Natural Asphalt: Trinidad Gilsonite
10.Antistrip	Amidoamines Hydrated lime Imidazolines Polyamines Organo-metallics

plastics, where it is strictly a pigment and limited to lower loadings. The rubber polymer forms strong chemical bonds with the carbon black, which accounts for its reinforcing ability [9]. The concept of using carbon black as a reinforcing agent in rubber has led to the concept of asphalt reinforcement.

Microfil 8 is a grade of pelletized carbon black specially designed as a microfiller for asphalt pavement mixture. It is a mixture of approximately 92% high structure, high abrasion furnace (HAF) type of carbon black with approximately 8% high durability Cabot oil which is similar to the maltene portion of asphalt.

A lot of researchers have reported the beneficial effect of carbon black in improving asphalt pavement performance [7,10,11,12,13]. Rostler et al. [10] have demonstrated the feasibility of carbon black as a reinforcing agent to increase the wear resistance of asphalts. Vallergia and Gridley [11] also have reported the beneficial effect of carbon black on the durability and the temperature-viscosity susceptibility of asphalts, and on the wear resistance and stability of asphalt concrete. Yao and Monismith [12] stated that the addition of carbon black in the form of microfil 8 in the amount of 15 to 20 percent by weight of the binder improved the fatigue life, resilient modulus, and resistance to rutting of asphaltic mixtures. Khosla and Zahran [13] showed that the addition of carbon black to the conventional asphalt cements reduced its temperature susceptibility and the permanent deformation of the paving mixtures and improved the fatigue life of the pavements, and increased the serviceability index of pavements. Tayebali et al.[14] conducted several tests to investigate the influence of Microfil 8 and polymer on AR-2000 asphalt. The results based on dynamic tests indicated that the loss tangent vs. temperature relationships for AR-2000 modified with 20 percent Microfil 8 are similar to those of 6 percent K4460 polymer modified AR-2000 asphalt. Button et al.[15] found that the addition of 15 percent microfil 8 in soft AC-5 asphalt had significantly higher resistance to permanent deformation than that of unmodified AC-20 asphalt.

It seems reasonable to conclude that the addition of a certain amount of microfil 8 carbon black to asphalt binder is beneficial to asphalt pavements by

(1) improving the resistance to fatigue cracking,
(2) reducing the load-associated permanent deformation,
(3) improving mix durability and wear resistance, and
(4) reducing sensitivity to water.

2.2.2 Effects of Polymers

2.2.2.1 Classification

A polymer is a large molecule that is formed from approximately hundreds to thousands of small molecules (monomers) held together by chemical bonds along the molecules to form linear or branched chains or a three-dimensional polymer network [16]. The process of forming polymeric chains is called 'polymerization'. The physical properties of a polymer are dependent on the chemical structure of the molecules of which it is made. Polymers can be divided into three distinct groups [16,17,18,19]: thermoplastics, thermosets and elastomers (rubbers) as shown in Figure 2.1.

Polymer is attracting wide attention and increased application in asphalts. As mentioned previously, conventional asphalts tend towards a glassy brittle state at low temperature, and at high temperature they become soft and fluid. It is evident that the use of polymers enhances the rheological properties of asphalt. A few states' highway departments have reported the successful application of polymers in asphalt mixtures to improve their highway performance [7], but others do not. Haas et al. [2,3] indicated that polymer modified asphalt is good for interlayers to limit reflection cracking through overlays. Kelly and Bresson [20] stated that the asphalt modified with block copolymers improved low temperature flexibility and increased strength at high service temperatures. They found that block copolymers can be successfully applied on highway joint sealants, paving repair, barrier membranes, and as surface dressings in the rejuvenation or repair of road surfaces. Goodrich [21,22] investigated several polymer-modified asphalts using dynamic mechanical analysis to

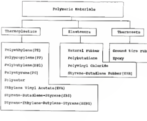


Figure 2 1 Classification of polymeric materials characterize the influence of polymer on asphalt binder. Goodrich found that at temperature below 10°C, the properties of modified asphalts are influenced by the asphalt itself but are influenced by the polymers at temperature above 10°C. This means that the polymer would not increase the viscosity of the asphalt binder at low temperature yet increase the permanent deformation resistance at high service temperature. The temperature susceptibility is reduced or the pen-vis number(PVN) is increased. Generally, the modifiers increase the viscosity at high pavement service temperatures to resist rutting and/or shoving, while not considerably affecting the cracking resistance of the low-viscosity base asphalt at low ambient temperature.

Several studies [19,23,5] were conducted comparing conventional asphalt cements with different modified asphalts with different concentration of polymers. It was concluded that an asphalt mixture with a proper amount of polymer will substantially improve the physical properties of the binder; the softening points are considerably elevated, the low temperature resistance is markedly improved, and the penetration is reduced. King et al.[24] also indicated that a proper asphalt mixed with an appropriate type and amount of polymer plays an important role in modified asphalt pavement.

2.2.2.2 Thermoplastic

Thermoplastics are linear or branched polymers which would soften upon heating and then could be made to flow when stress is applied [17,18]. When cooled again, they would reversibly regain their solid or rubbery nature, such as styrene-butadiene-styrene(SBS), styrene-ethylene-butylene-styrene(SEBS), ethylene-vinyl-acetate(EVA), etc. At a sufficiently low temperature, all thermoplastic polymers behave as if they were solids, but as the temperature is raised toward the glass transition temperature(Tg), they become ductile. Such polymers impart quick early strength to the system under loading. Therefore, thermoplastic polymers provide a pavement with a high stiffness modulus and higher stability, while elastomers and thermosets give a more resilient, flexible pavement. Generally, a thermoplastic should be selected when small strain and maximum stability are required for the asphalt mixtures.

Styrene ethylene butylene styrene (SEBS) is formed by linking two diblocks, where it is made by polymerising ethylene-butylene rubber to block copolymer styrene [18]. This is different from a standard randomly copolymerized system like styrene-butadiene rubber (SBR) which gives a response intermediate between the two polymers (polystrene and polybutadiene).

SEBS thermoplastic block copolymers in general exhibit excellent tensile strength [18], which is similar to that of vulcanized rubber but it does not require vulcanization. Collins and Mikols [23] found that the addition of SEBS polymers to an asphalt binder system can provide a reduced penetration, increased softening point, improved low temperature ductility, increased toughness and tenacity, and increased viscosity at high temperature. Carpenter and Vendam [25] conducted a laboratory performance study to compare a polymer-modified asphalt and an unmodified asphalt. They found that the polymer modified asphalt reduced stiffness at low temperatures and maintained adequate stiffness at elevated temperatures. This indicated that the potential for low temperature thermal cracking was significantly reduced, and the permanent deformation characteristics were greatly improved by the polymer-modified asphalt. Shuler et al. [5] reported that the polymer-modified asphalt is less temperature susceptible than that of an unmodified asphalt from 0°C (32°F) to 93°C (200°F).

2.2.2.3 Elastomer

Elastomers are lightly cross-linked polymers which can be defined as materials capable of fairly large elastic deformations [18]. From the standpoint of modulus, an elastomer is a rubber-like material but has limited extensibility and incomplete retraction. Important types of elastomers include natural rubber, styrene butadiene rubber (SBR), etc. These polymers impart very little strength to the system until they are stretched but their tensile strength are increased with elongation. In contrast, the strengths of thermoplastics are limited after elongation.

Styrene butadiene rubber (SBR) was developed in Germany under the name "BUNA-S" and in North America, during World War II, as "GR-S" (government rubber-styrene) [16,18]. SBR is the most widely used rubber in the entire world. It is a random copolymer of styrene and butadiene made by free radical copolymerization in emulsion [17]. Button et al.[15] studied several modified asphalts using a force ductility test to measure tensile load-deformation characteristics of asphalt and modified asphalts. They found that asphalt containing SBR exhibited marked increases in energy required to produce failure. Verga et al. [26] found that at low temperatures the SBR elastomers do not increase the asphalt rigidity, but at higher temperatures the rubberized asphalt is more rigid than the unmodified one. This is significant for preventing rutting in asphalt concrete. Field construction projects have been done by Krater et al. [27]. They found that the addition of polyolefin and styrene butadiene rubber in certain combinations will increase resistance to rutting while it does not increase thermal cracking at low temperatures. It also reduces moisture susceptibility.

2.2.2.4 Thermoset

Thermosets are rigid, highly cross-linked polymers which are produced by the direct formation of network polymers from small molecules, or cross-linking linear polymers. Once formed the polymer cannot be returned to a plastic state by heating [18]. Such polymers will deform immediately under a given load but recover to their original configuration when the load is removed, as in the case of tire rubber.

A rubber is generally defined as a material that can be stretched to at least two times its original length and that will retract rapidly to its original shape after the force is released. From a molecular standpoint [18], a rubber consists of long flexible chain-like molecules which are interconnected at various points by cross-linking to form a loose molecular network. The denser the network chain is, the greater its resistance to further pulling, since rubber elasticity is due mainly to this network [16,17].

Natural rubber did not achieve any commerical significance until Goodyear [18] cross-linked (vulcanization) it into a highly elastic network to produce tire rubber.

Ground tire rubber has been blended with asphalt cement and used in various types of pavement construction such as seal coat, interlayer [28,29,30,31], and more recently as surface course, open-graded friction course [32-41]. Because of the improved elasticity imparted to the binder, it is believed that the addition of rubber can increase the amount of energy it can absorb before failing. Many researchers and producers have reported many benefits of adding rubber to asphalt mixtures, such as reduced penetration [31,33,39], reduced temperature susceptibility [34,39], increased softening point [31,33,34,39], increased absolute viscosity [28,30,31,33,34,41], and increased resilient modulus

[34,36,41]. These improved characteristics make the pavement better able to resist either cracking or deformation. For instance, the increased viscosity at high service temperature results in greater flow resistance of binder and hence reduce the rutting problem. However, some researchers [13,42,43,44,45] stated that the major disadvantage of using rubber modified asphalt is the high cost. The initial cost of rubber asphalt mixture is higher than that of conventional asphalt concrete by approximately 15 percent to 30 percent.

2.3 Effects of Modified Asphalts on Open-graded Mixes

Open-graded asphalt mixtures have been characterized by adding a large proportion of single-sized coarse aggregate to provide the excellent macrotexture (stone projections) and necessary microtexture (harshness) properties without assistance from the fine aggregate and small amount of fine aggregate to provide a "choking action" for the stabilization of the coarse aggregate fraction [46,47]. The role of the macrotexture is to provide drainage channels so that most of the water can be drained from the contact area between the rolling tire and the pavement surface. The microtexture allows penetration of the remaining thin film of water on the roadway surface. FHWA [46] recommended that relatively pure carbonate aggregates or any aggregates known to polish should be excluded from the coarse aggregate fraction of the open-graded friction course (material retained on No. 8 sieve). Also, the coarse aggregate fraction should have at least 75 percent by weight of particles with at least two fractured faces and 90 percent with one or more fractured faces and the abrasion loss, as determined by AASHTO T96, should not exceed 40 percent. Similar recommendations have been reported by Kazei et al. [46], Tam and Lynch [45], and Hamdani [50].

For friction courses, the optimum asphalt content of open-graded asphalt mixtures is usually based on empirical formulae which were developed from field experience. These formulae are mainly a function of the surface capacity (K_c) of the coarse aggregate fraction of the mixture. The FHWA (46) procedure uses the following equation:

$$AC = (2K_c + 4.0) \times 2.65/SG_{ca}$$

where

AC= asphalt content (by weight of aggregate)

K_c= surface capacity of the coarse aggregate fraction, which is based on Hveem design procedure

SG_{ca}= apparent specific gravity of coarse aggregate

The general advantages of using open-graded mixes as friction courses are as follows [46,47,51]:

(a) High skid resistance at high speeds during wet weather

(b) Reduction of splash and spray during wet weather

(c) Reduction of wheel path rutting

(d) Reduction of hydroplaning effects on wet pavement

(e) Reduction of light reflection from wet pavement

(f) Reduction of tire rolling noise

All of these benefits have been proved by many researchers [48,49,50,52,53].

The major disadvantages of open-graded mixes are mainly their poor durability and stripping problem. Their high air voids (a minimum of 15 percent as recommended by the FHWA procedure) and thin asphalt film can cause rapid disintegration of the mix. Gemayel and Mamlouk [54] pointed out that the open-graded asphalt mixture is more temperature susceptible than that of dense-graded asphalt concrete.

There is little literature on modified asphalt used in the open-graded mixtures in the United States. Most of the available literature on the open-graded mixtures is based on conventional unmodified asphalt and usually is concerned with emulsion mixtures [55]. However, modified asphalts employed in the open-graded mixes have been widely used in Europe for many years, where the thickness of the friction course is around twice as thick as that in the United States. The primary purpose for using modified asphalt on open-graded mixes is to eliminate or minimize the disadvantages and also maintain or improve the advantages of that of conventional open-graded mixes. Perez-Jimenez and Gordillo [56] conducted a Cantabro test of wear loss, which consisted of introducing Marshall samples before and after water immersion into the Los Angeles machine (without balls) to obtain their weight loss after 300 drum revolutions to evaluate the disintegration resistance and adhesiveness of polymer-modified asphalt on the manufacturing of open-graded mixes. They observed that the mix manufactured with polymer improved the resistance of disintegration and adhesiveness. Ruiz et al. [57] stated that the advantage of using modified binder in open-graded mixes is to get longer durability through thicker films of binder because of high viscosity, and to reduce the temperature susceptibility of the mix. Huet et al. [58] carried out a fatigue test track to evaluate the fatigue behavior of conventional asphalt, SBS modified asphalt, and fiber modified asphalt on road structures. The test results from their work indicated that the drainage properties were practically unchanged and rutting was minimized by the use of fiber-based binder and SBS modified asphalt. Sainton [59] stated that asphalt modified with rubber has high cohesion, high flexibility at low temperature, strong cracking resistance, and remarkable aging resistance because of an antioxidant in the rubber powder. Because of the improved rheological properties of the modified binder, it is easy to obtain a greater thickness of the binder film, which leads to improved cohesion, and durability of the mix.

2.4 Viscoelastic Properties of Modified Asphalts

A distinctive feature of the mechanical behavior of viscoelastic materials is that their response to an applied stress or strain depends on the loading rate or the time duration of loading [60]. Basically, elastic materials follow Hooke's law, where the stress is proportional to the strain; in contrast, viscous materials tend to obey Newton's law, with the stress being proportional to the rate of strain and independent of the strain. The behavior of viscoelastic materials is somewhere between that of elastic solids and viscous liquids, which means that these materials exhibit both solid and liquid behavior [60,61]. At high temperatures, they usually behave in a Newtonian manner. As the temperature decreases, they usually show an increasing degree of non-Newtonian behavior. However, the transition from non-Newtonian to Newtonian behavior is gradual, and the rate of change from one state to another is a function of the composition and the type of the material. For Newtonian fluids, a plot of shear stress versus shear rate is represented by a straight line through the origin. The slope of this line is the viscosity. For non-Newtonian fluids, the relationship between shear stress versus shear rate is usually not represented by a straight line.

To explain the observed mechanical behavior of bitumens, several rheological models have been proposed [62]. Basically, these models consist of various combinations of elastic springs and viscous dashpots. The spring and dashpot elements combined in different ways are a useful tool to describe the form of the stress-strain relationship for linear viscoelastic behavior. The spring on its own is not useful because it does not describe the time-dependent behavior, nor can the dashpot alone describe recovery behavior. However, the Maxwell model which consists of a spring and a dashpot in series does not display complete recovery. The Voigt model consists of the same fundamental elements as the Maxwell model except that the spring and dashpot are in parallel instead of in series. This model is also flawed because it does not describe stress relaxation under constant deformation. Thus, these simple models do not provide adequate approximations of the behavior of viscoelastic materials.

In order to overcome these deficiencies, models such as Burger's have been proposed, which combine elements of the Maxwell and Voigt versions. Brown and Spark [63] employed as many as four Kelvin elements into Burger's model to describe step by step the development of the rheological pattern of viscoelastic material. Secor and Monismith [64] used a four-element model similar to Burger's model to describe the rheological behavior of viscoelastic materials. In this model, the top spring mechanically represents the purely elastic deformation, the combined middle spring and dashpot represent the delayed elastic deformation, and the lower dashpot represents the purely viscous flow deformation. Monismith et al. [62] further noted that this model has limitations over an extended period of time even though it can predict the results of three tests to a reasonable degree. To remedy this, they increased the number of elements and developed a generalized model to compare the measured and predicted data for creep, stress relaxation, and constant rate-of-strain triaxial tests. This appears to be a valid model which reasonably represents the influence of time of loading and temperature on the stress-strain characteristics of viscoelastic materials. Further, Majidzadeh and Schweyer [65] refined this idea and developed a generalized Maxwell-multiple Kelvin model to evaluate the complex modulus and its components for four different asphalt cements.

Noting the many possible combinations of springs and dashpots, Kuhn and Rigden [66] suggested that a model which successfully explains the viscoelastic properties of bitumen should include the following features:

(1) The model must include an "outside dashpot" to provide the indefinite flow of bitumens under the stress.

(2) The model needs an "outside spring" because the material tends more and more toward the state of an ideal elastic solid as the rates of loading increase.

(3) The model should provide for the delayed deformation after the application of a steady stress.

(4) At the same time, the model should provide for the instantaneous deformation to occur on impact, so that all the springs must not be protected by dashpots.

(5) The model should show a continuous increase in fracture strength with increase in rate of loading up to a limiting value.

However, by assuming the bitumen to be a Newtonian material, the problem of the shear susceptibility of the asphalt cement has been conveniently neglected. Hence, none of the developed models defined the flow regime. Schweyer and Burns [67] and Schweyer et al. [68] therefore pointed out that the factors such as shear susceptibility, variations in viscosity with shear rate, temperature, and pressure all affect stiffness of material. Because of this, they proposed a model to accommodate the effects of the stress level on the shear strain rate. The Burn-Schweyer model is a modified Burger's rheological model for a non-Newtonian material. In the H-S model, the lower dashpot has been modified to incorporate into the system a feedback mechanism which adjusts the lower dashpot viscosity to accommodate the type of non-Newtonian flow involved.

In addition to creep and stress relaxation experiments, it is also possible to define the rheological response of viscoelastic materials using dynamic mechanical tests [60,61]. In such tests a sinusoidally varying stress or strain is applied to a specimen, and the corresponding sinusoidally varying strain or stress is measured. If the material is linearly viscoelastic and the input is sinusoidal stress, the strain response will be the same as the sinusoidal but out of phase with the stress by an angle between 0 and 90, called the loss angle δ [60,61]. It is usually analyzed by a diagram plotting the logarithm of the complex modulus G^* versus logarithm frequency. Pagan [69], Coffman and Craft [70], Monismith et al. [62], Jongepier and Kuilman [71], Goodrich [72], and Christensen and Anderson [73] have used this dynamic test method to define the rheological response of asphalt concrete.

2.5 Effects of Artifical Weathering on Modified Asphalts

Durability has been defined as the resistance to change in physico-chemical properties of asphalt with time under the action of weather and traffic [1]. Asphalt hardening is a very important factor in causing asphalt pavement to crack and disintegrate. Because the rate of asphalt hardening in service has been recognized as the major factor affecting the durability of an asphalt, many durability tests are based on the evaluation of resistance to asphalt hardening

In order to investigate the durability of asphalt cements, it is essential to understand the physico-chemical behavior of the asphalts. Chemical change such as oxidation is thought to be the immediate cause of asphalt composition alterations. These changes create marked differences in the rheological properties of asphalt cements and result in irreversible hardening. It has been claimed that this oxidative hardening is mainly due to the formation of highly polar, strongly oxygen-contained chemical functionality with the asphalt molecules [74,75,76]. According to Ishai and his coworkers [77,78,79,80], the diffusion rate of oxygen into the asphalt binder and the reactivity of asphalt cement determine the oxidation reaction. In contrast, the physical changes taking place in reversible hardening are attributed primarily to rearrangement or reorientation of the micelles and often occur when the asphalt is in a continuous state of deformation.

It is evident that physico-chemical factors provide a useful tool for characterizing the durability of asphalt cements. Petersen [81] and Petersen et al. [82] recently reported that physico-chemical factors between oxygen and asphalt molecules control the kinetics of age-hardening of asphalt cements rather than the intrinsic reactivity of the molecular components with oxygen. He indicated that the age-hardening kinetics of asphalt cements is controlled by the state of dispersion of associated molecules in asphalt instead of by the inherent reactivity of the components with oxygen. However, Robertson et al. [83], in an SHRP project regarding the relationship between the chemical composition and physical properties of new and aged asphalt using the pressure air vessel test (PAV) and modified rolling-thin-film-oven-test (RTFOT) equipments to simulate pavement oxidation, observed that the chemical and physical properties among asphalts are quite different from one another. These disparate laboratory results lead to the conclusion that reliable and practical information is obtained only when the behavior of asphalt in the durability test can be correlated with pavement durability in the field.

Long-term age hardening testing of asphalt in the laboratory has been a quite promising approach to investigating the durability of asphalts. However, conventional evaluation within single-temperature and single-time domain is severely limited as a sensible and extensive evaluation of asphalt aging. Ishai [84] suggested that the temperature-time domain should be characterized and investigated over a wide range of oven temperature and exposure durations. He and his coworkers [77,78,79,80] found that the aging mechanisms of asphalt at too high temperature levels employed in accelerated conditions are believed not to differ significantly from those occurring under the relatively mild conditions in the field. Recent research at the University of Florida [85,86,87] on age-hardening of asphalt binder indicates that temperature plays a major role in changing the rheological properties of aged asphalts and in simulating long-term field aging. To accelerate the aging condition, the temperature for performing TFOT and RTFOT tests can be increased. Page et al. [88] also suggests that the TFOT and RTFOT test temperature can be enhanced to aid in identifying the amount of hardening that occurs at specific plant mixing temperatures.

CHAPTER 3
RESEARCH TESTING PROGRAM

3.1 Research Program

The work to be performed in this study consists of the following subtasks:

(1) Evaluation of the effects of selected modifiers on the temperature susceptibility of typical asphalt cements

(2) Evaluation of the aging characteristics of modified asphalt binders.

(3) Evaluation of the aging characteristics of modified asphalt mixtures.

Figure 3.1 shows the key elements of this research program.

3.2 Evaluation of the Effects of Selected Modifiers on the Temperature Susceptibility of Typical Asphalt Cements

Seven types of modifiers which appear likely to improve the resistance to rutting and/or cracking, stripping were selected for this study. These seven modifiers were:

(1) Gilsonite

(2) Carbon Black

(3) Fine Ground Tire Rubber (GTR-80)

(4) Coarse Ground Tire Rubber (GTR-40)

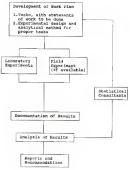

Development of Work Plan
1.Tasks, with statements of work to be done
2.Experimental design and analytical method for proper tasks
Laboratory Experiments
Field Experiment (if available)
Statistical Consultants
Documentation of Results
Analysis of Results
Reports and Recommendations

Figure 3.1 Summary of the Research Program for This Study

(5) Styrene-Butadiene Rubber (SBR)

(6) Ethylene Vinyl Acetate (EVA)

(7) Styrene-Ethylene-Butylene-Styrene (SEBS)

Five of the seven selected modifiers including gilsonite, carbon black, GTR-80, GTR-40, and SBR modifiers were blended with an AC-30 asphalt cement using three different levels of addition of modifier, and the other two modifiers were blended with three different grades of asphalt cements namely, AC-30, AC-20, and AC-5, using one level of addition of modifier to produce a total of 21 different blends of modified asphalt. One of the levels of addition of GTR-80 was 5 percent, and one of the levels of addition of GTR-40 was 15 percent, which are typical amounts used in Florida. These 21 modified asphalt blends and the unmodified control AC-30, AC-20, and AC-5 asphalt were subjected to the TFOT procedure at 163°C (325°F). The following tests were performed on the 24 original asphalt blends and the 24 residues from the TFOT:

(1) Kinematic viscosity at 135°C (275°F).

(2) Absolute viscosity at 60°C (140°F).

(3) Schweyer rheometer tests at 5° and 25°C (41 and 77°F).

(4) Penetration at 4° and 25°C (39.2 and 77°F).

(5) IR spectral analysis.

The five modifiers were also blended with the AC-20 using one level of addition to produce a total of five blends of modified AC-20 asphalt. The levels of addition of GTR-80 and

GTR-40 was 5 and 15 percent, respectively. These five modified asphalts were subjected to the TFOT procedure at 163°C (325°F), and the five tests as listed above were conducted on the five original asphalt blends and the five residues from the TFOT.

In this test series, there was a total of 31 original asphalt blends and 31 residues from the TFOT to be tested for the study of the effects of the modifiers on the temperature susceptibility of asphalt binders. Figure 3.2 shows the flow chart of this subtask.

3.3 Evaluation of the Aging Characteristics of Modified Asphalt Binders

Twelve asphalt blends were used in this test series to evaluate the effects of TFOT and RTFOT temperatures on the aged-hardening characteristics of modified asphalts. The twelve binders include a control AC-30, AC-30 modified with gilsonite, carbon black, GTR-80, GTR-40, SBR, EVA, and SEBS, AC-20 modified with EVA and SEBS, and AC-5 modified with EVA and SEBS. Figure 3.3 shows the summary of the testing program for this subtask.

The control AC-30, carbon black modified, and gilsonite modified asphalts were subjected to the following aging procedures:

(1) TFOT at 141°C (285°F).

(2) TFOT at 185°C (365°F).

(3) RTFOT at 141°C (285°F).

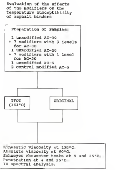

Subtask I
Evaluation of the effects of the modifiers on the temperature susceptibility of asphalt binders
Preparation of Samples
1 unmodified AC-30
+ 7 modifiers with 3 levels for AC-30
1 unmodified AC-20
+ 7 modifiers with 1 level for AC-20
1 unmodified AC-5
2 control modified AC-5
TFOT (163°C)
ORIGINAL
Kinematic viscosity at 135°C.
Absolute viscosity at 60°C.
Schweyer rheometer tests at 5 and 25°C.
Penetration at 4 and 25°C.
IR spectral analysis.

Figure 3.2 Flow chart of activities in subtask I

Subtask II

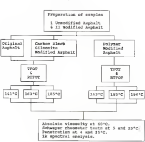


Figure 3.3 Flow chart of activities in subtask II.

(4) RTFOT at 163°C (325°F).

(5) RTFOT at 185°C (365°F).

The other nine polymer modified asphalts were subjected to the following aging procedures:

(1) TFOT at 185°C (365°F).

(2) TFOT at 196°C (385°F).

(3) RTFOT at 163°C (325°F).

(4) RTFOT at 185°C (365°F).

(5) RTFOT at 196°C (385°F).

The following tests were performed on the 12 original asphalt blends and (12x5) 60 asphalt residues from the TFOT and RTFOT:

(1) Absolute viscosity at 60°C (140°F).

(2) Schweyer rheometer tests at 5° and 25°C (41° and 77°F).

(3) Penetration at 4° and 25°C (39.2° and 77°F).

(4) IR spectral analysis.

3.4 Evaluation of the Aging Characteristics of Modified Asphalt Mixtures

The eleven modified asphalts and the unmodified AC-30 used in subtask (2) was used to make Florida S-1 and FC-2 mixes. These mixtures were compacted into Marshall specimens for age hardening and subsequent testing. The compacted asphalt mix specimens made with unmodified AC-30 and seven modified asphalts (AC-30 plus gilsonite, carbon black, GTR-80, GTR-40, SBR, EVA, and SEBS modifier) were subjected to the following aging conditions:

(1) Aging in a forced-draft oven at 60°C (140°F) for 90 days.

(2) Aging under natural sunlight for 6 months, 1, and 2 years.

(3) No aging.

The mixtures made with the other four modified asphalts were aged in a forced-draft oven at 60°C (140°F) for 90 days, no aging, and under sunlight for 6 months only. Four replicate specimens were made for each condition. This amounted to a total of ((5x8+12)x4x2) 416 specimens for this part of the study. Figure 3.4 shows the testing program of the asphalt mixtures.

For each type of mixture, two extra samples were made in order to run the Rice specific gravity tests. Thus, the grand total number of samples made was (416 + 2x24) 464.

The following tests were performed on the Marshall specimens:

(1) Resilient modulus tests at 5° and 25°C (41 and 77°F).

(2) Indirect tensile tests at 5°C (41°F) on two replicate specimens.

(3) Indirect tensile tests at 25°C (77°F) on two replicate specimens.

After the specimens was broken in the indirect tensile tests, the asphalt binder was recovered from the asphalt mixtures. The following tests were performed on the recovered asphalt residues:

Subtask III

Testing Program on Asphalt Mixtures

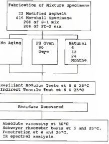

Fabrication of Mixture Specimens
12 Modified Asphalt
416 Marshall Specimens
208 of S-1 mix
208 of FC-2 mix
No Aging
FD Oven
90
Days
Natural
6
12
24
Months
Resilient Modulus Tests at 5 & 25°C
Indirect Tensile Test at 5 & 25°C
Residues Recovered
Absolute viscosity at 60°C
Schweyer rheometer tests at 5 and 25°C.
Penetration at 4 and 25°C.
IR spectral analysis.

Figure 3.4 Flow chart of activities in subtask III.

(1) Absolute viscosity at 60°C (140°F).

(2) Schweyer rheometer tests at 5° and 25°C (41 and 77°F).

(3) Penetration at 25°C (77°F).

(4) IR spectral analysis.

CHAPTER 4
MATERIALS AND LABORATORY PROCEDURES

This chapter presents the materials and procedures used in this laboratory testing program. It includes a description of the properties of asphalt binders, modifiers, and aggregates, the fabrication of Marshall specimens, the tests on Marshall specimens, and the tests on the aged asphalt residues.

4.1 Materials

4.1.1 Modifiers

Seven different modifiers were used. They are (1) gilsonite, (2) carbon black, (3) two types of ground tire rubbers, (4) styrene butadiene rubber (SBR), (5) ethylene vinyl acetate (EVA), and (6) styrene ethylene butylene styrene (SEBS).

Gilsonite, which is a natural hard asphalt, was obtained from Ziegler Chemical Mineral Corporation. The carbon black used was a product by the name of Microfil-8, which was supplied by Cabot Corporation. Microfil-8 is in the form of pellets, and is a mixture of approximately 92% high structure, high abrasion furnace (HAF) type of carbon black with approximately 8% high durability Cabot oil. Ground tire rubbers of thermoset polymeric materials , were supplied by two sources. One was a fine ground tire rubber (#80) in the form of powder supplied by Rouse Rubber Industries. The other was a coarse ground tire rubber (#40) in the form of crumb, from Baker Rubber Corporation. Elastomeric SBR in the form of a latex was supplied by BASF Corporation. Thermoplastic block copolymer SEBS was obtained from Shell Oil Company. The flexible thermoplastic copolymer EVA was supplied by Exxon Chemical Americas. The blending of asphalt with both thermoplastic copolymers, SEBS and EVA, were done by the manufacturers. Table 4.1 lists the manufacturers for each modifier.

4.1.2 Asphalts

Three different grades of paving asphalt were used. They were AC-30, AC-20, and AC-5 which meet the Florida Department of Transportation specifications. The modified asphalt binders were made by blending different amounts of modifier with different types of asphalt. A total of 31 modified asphalt binders were used in this study. Table 4.2 lists the different amounts of modifier used in the different types of asphalt binders along with the specific gravity for each modified asphalt binder.

4.1.3 Aggregates

The aggregates used in the mixture tests were obtained from two different sources. Aggregates from one source were used to make dense-graded mixes meeting Florida S-1 specifications. They were a Florida Mining Materials #67 stone, S1-B, screening, a Canal Auth sand, and a mineral

Table 4.1 Modifiers used in the study

Modifier	Modifier Type	Producer
1.	Gilsonite	Ziegler Chemical Mineral Corp.
2.	Carbon Black	Cabot Corp
3.	GTR-80	Rouse Rubber Corp
4.	GTR-40	Baker Corp.
5.	SBR (Latex)	BASF Corp.
6.	EVA	Exxon Chemical Americas
7.	SEBS	Shell Chemical Company

Table 4.2 List of modified asphalt binders tested.

Asphalt	Abbreviation	Specific gravity
AC-30	A	1.045
+ 5% Gilsonite *	A5G	1.031
+ 10% Gilsonite	A10G	1.030
+ 15% Gilsonite	A15G	1.020
+ 5% Carbon Black	A5C	1.073
+ 10% Carbon Black *	A10C	1.084
+ 15% Carbon Black	A15C	1.085
+ 2% GTR-80	A2R8	1.046
+ 5% GTR-80 *	A5R8	1.034
+ 8% GTR-80	A8R8	1.027
+ 10% GTR-40	A10R4	1.040
+ 15% GTR-40 *	A15R4	1.047
+ 20% GTR-40	A20R4	1.070
+ 2% SBS	A2SB	1.030
+ 3.5% SBS *	A35SB	1.027
+ 5% SBS	A5SB	1.027
+ 5% EVA *	A5E	1.039
+ 5% SEBS *	A5SE	1.018
AC-20	B	1.043
+ 5% Gilsonite	B5G	1.029
+ 10% Carbon Black	B10C	1.069
+ 5% GTR-80	B5R8	1.028
+ 15% GTR-40	B15R4	1.026
+ 3.5% SBS	B35SB	1.030
+ 3% EVA	B3E	1.033
+ 5% EVA *	B5E	1.027
+ 8% EVA	B8E	1.019
+ 3.5% SEBS *	B35SE	1.034
AC-5	C	1.020
+ 5% EVA *	C5E	1.007
+ 3.5% SEBS *	C35SE	1.006

* ASPHALT BLENDS USED FOR MARSHALL SPECIMENS

filler. The aggregates from second source, which consist of two types of aggregate and a mineral filler, were used to make open-graded mixes meeting Florida FC-2 specifications. Table 4.3 lists the aggregate types and blends used, as well as job mix formula for the S-1 mixes. Table 4.4 shows the aggregate types, blends used, and job mix formula for the FC-2 mixes.

4.1.2 Marshall Specimens

Among the 31 modified asphalt binders evaluated by the binder tests, twelve asphalt blends were selected and used to make Florida type S-1 and FC-2 asphalt concrete mixes, which were compacted into Marshall specimens. A total of 416 Marshall specimens, consisting of 208 specimens of dense-graded mixes and 208 specimens of open-graded mixes, were prepared.

A Marshall mix design was performed to determine the optimum asphalt content for the dense-graded mix. Table 4.5 summarizes the material properties of the Marshall mix design. An optimum asphalt content of 6.5 percent was obtained for the S-1 mix. Therefore, a 6.5 percent asphalt content was adopted for the dense-graded mixtures made with these modified binders with the exception of coarse ground tire rubber where 7.0 percent asphalt content was used, because the coarse rubber (#40) particles create more surface area that must be coated. For the open-graded mixes, Marshall specimens were fabricated with an asphalt content of 6.3 percent and compacted by 50-blow Marshall compaction. The corresponding mixing

Table 4.3 Source of Aggregates and Job Mix Formula for Dense-graded Mixes.

Number	Aggregate Type	Producer	Pit No.
1.	#67 Stone	Florida Mining & Materials	08-005
2.	S1-8	Florida Mining & Materials	08-005
3.	Screening	Florida Mining & Materials	08-005
4.	Canal Auth Sand		
5.	Mineral filler		

Aggregate Gradation

Blend	20%	25%	35%	18%	2%	Job mix	Spec.
Agg.	#67	S-18	Scr	Sand	MF	formula	S-I
Sieve			(% passing)				
3/4"	100	100	100	100	100	100	100
1/2"	65.41	100	100	100	100	67.06	66-100
3/8"	52.32	64.05	100	100	100	66.96	75-93
#4	5.38	19.73	66.66	100	100	60.64	47-75
#10	1.74	2.94	66.03	100	100	45.24	31-53
#40	1.65	1.76	16.64	88.71	100	25.33	19-35
#60	1.54	1.57	6.66	16.72	100	8.58	7-21
#200	1.06	1.18	4.05	1.73	100	4.24	2-6
Spec Grav	2.362	2.307	2.312	2.645	2.653		

Table 4.4 Source of Aggregates and Job Mix Formula for Open-graded Mixes.

Number	Aggregate Type	Producer	Pit No
1.	FC-2 Rock	Rinker Materials	87-090
2.	Medium Screening	Rinker Materials	87-090
3	Mineral filler (200 Bag house Dust)		

Aggregate Gradation

Blend	87%	11%	2%	Job mix	Spec.
Agg.	FC-2 Rock	Medium Screenings	Mineral filler	formula	FC-2
Sieve		(% passing)			
3/4"					
1/2"	100	100	100	100	100
3/8"	98.5	100	100	98.7	85-100
#4	3.57	98.87	100	15.45	10-40
#10	0.99	78.95	100	11.55	4-12
#40	0.97	36.24	100	5.83	
#80	0.86	13.59	100	4.23	
#200	0.55	1.39	100	2.63	2-5
Spec. Grav.	2.388	2.473	2.567		

Table 4.5 Marshall mix design properties.

Design asphalt content:	6.5 percent		
Mix properties at design:		Design Criteria	
		min	max
Unit weight	135.5 (pcf)		
Marshall stability	2751 (lb)	1500	---
Flow unit	8 (0.01 in)	8	16
Air void	4.56 percent	3	5
VMA	14.9 percent	14	---

temperatures to get a viscosity of 1.7 ± 0.2 poises, as recommended by the Asphalt Institute, for both mixtures on different asphalt blends was obtained from previous subtask I. Tables 4.6 and 4.7 list the asphalt contents as well as respective blending and mixing temperatures.

The maximum specific gravities of the mixes were determined by means of the Rice Method (ASTM D2041 or AASHTO T-209) for uncompacted asphalt porous-aggregate mixtures. Two samples were tested for each type of asphalt mix. Table 4.8 and Table 4.9 list the maximum specific gravities for the dense-graded and the open-graded mixes, respectively. The properties of the 504 dense-graded and open-graded Marshall specimens are shown in Appendixes A.1 and A.2, respectively.

4.2 Laboratory Procedures

4.2.1 Preparation of Modified Asphalts

The procedures for blending asphalts with modifiers consist of the following steps:

1. The selected modifier was weighed out in an open stainless steel beaker to the desired amount by means of balance.
2. The selected asphalt binder which is stored in a quarter pint aluminum can was heated to the desired blending temperature on a hot plate.
3. Place a variable-speed air-propeller mixer in the heated can. Turn on the pressure and adjust the air

Table 4.6 Asphalt Contents and Mixing temperatures of Binders Used in the Dense-Graded Mixtures

Asphalt Type	Asphalt Content (%)	Mixing Temperature Used (°F)	Optimum BlendingTemp. from BTDC (°F)
AC-30	6.5	300	310
AC-30 +5% Gilsonite	6.5	338	320
AC-30 +10% Carbon Black	6.5	330	320
AC-30 +5% GTR-80	6.5	375	340
AC-30 +15% GTR-40	7.0	375	410
AC-30 +3.5% SBR	6.5	375	385
AC-30 +5% EVA	6.5	375	350
AC-20 +5% EVA	6.5	375	340
AC-5 +5% EVA	6.5	375	340
AC-30 +5% SEBS	6.5	375	365
AC-20 +3.5% SEBS	6.5	375	360
AC-5 +3.5% SEBS	6.5	375	375

Table 4.7 Asphalt Contents and Mixing temperatures of Binders Used in the Open-Graded Mixtures

Asphalt Type	Asphalt Content (%)	Mixing Temperature Used (°F)	Optimum BlendingTemp from STDC (°F)
AC-30	6.3	300	310
AC-30 +5% Gilsonite	6.3	330	320
AC-30 +10% Carbon Black	6.3	330	320
AC-30 +5% GTR-80	6.3	375	340
AC-30 +15% GTR-40	6.3	375	410
AC-30 +3.5% SBR	6.3	375	385
AC-30 +5% EVA	6.3	375	350
AC-30 +5% SEBS	6.3	375	365
AC-20 +5% EVA	6.3	375	340
AC-5 +5% EVA	6.3	375	340
AC-20 +3.5% SEBS	6.3	375	360
AC-5 +3.5% SEBS	6.3	375	365

Table 4.8 Maximum Specific Gravities of Dense-Graded Mixtures

Mixture	Maximum Specific Gravity Rice Method (ASTM-2041)
AC-30	2.3150 2.3220
AC-30 + 10% Carbon Black	2.3040 2.3000
AC-30 + 5% Gilsonite	2.3045 2.3016
AC-30 + 5% GTR-80	2.2268 2.2265
AC-30 +15% GTR-40	2.2810 2.2822
AC-30 + 3.5% SBR	2.2896 2.2895
AC-30 + 5% EVA	2.3420 2.2180
AC-30 + 5% SEBS	2.2780 2.2710
AC-20 + 5% EVA	2.2887 2.2758
AC-20 + 3.5% SEBS	2.2600 2.2710
AC-5 + 5% EVA	2.2880 2.2800
AC-5 + 3.5% SEBS	2.2660 2.2750

Table 4.9 Maximum Specific Gravities of Open-Graded Mixtures

Mixture	Maximum Specific Gravity Rice Method (ASTM D-2041)
AC-30	2.2232 2.2154
AC-30 + 10% Carbon Black	2.2368 2.2423
AC-30 + 5% Gilsonite	2.2282 2.2181
AC-30 + 5% GTR-80	2.2215 2.2286
AC-30 +15% GTR-40	2.2360 2.2310
AC-30 + 3.5% SBR	2.2230 2.2220
AC-30 + 5% EVA	2.2300 2.2290
AC-30 + 5% SEBS	2.2360 2.2280

pressure until the desired speed is reached. For the propeller mixer used, a pressure of 15 psi was used for normal modifiers and 20 psi was used for polymer modifiers. The selected and weighed modifier was gradually poured into heated asphalt binder and then mixed. The desired temperature was maintained while the modifier was added.

4. The entire mixing process takes approximately 20 minutes for regular modifiers.

For thermoset polymer and thermoplastic block copolymer modifiers, the following additional procedures are needed:

5. A high shear rate is required for mixing polymer modifiers with asphalt.
6. After 20 minutes of mixing, the asphalt blend was kept at the desired temperature for 20 minutes to allow the reaction between the asphalt and the polymer-chain.
7. After the polymer-asphalt reaction, the asphalt blend was mixed for another 20 minutes to have a better blending.
8. The blended modified asphalt was poured out right after mixing for preparation of binder tests.

4.2.2 Preparation of Marshall Specimens

The procedures for the fabrication of Marshall specimens made with the modified asphalt binders are as follows:

1. The properly batched aggregate blend was placed in

an oven at the desired temperature for at least 3 hours to ensure that the aggregate is hot and dry.

2. Standard Marshall molds of 4 inches in diameter were placed in an oven at the desired temperature for 3 hours.
3. The modified asphalt blend was heated to the desired temperature before mixing.
4. The preheated aggregates were mixed with the modified asphalt in an asphalt mixer for approximately 2 minutes.
5. The prepared mixture was placed in the mold. Fifty blows were applied to each side with a Marshall hammer assembly at the selected compaction temperature.
6. In the case of rubberized asphalt mixtures, a 4-inch diameter concrete cylinder was placed on top of the compacted specimen in the mold right after compaction to prevent the specimen from swelling.
7. After cooling down to room temperature, the cooled specimens were extruded from the molds by means of an extrusion jack.
8. The bulk specific gravity was determined in accordance with ASTM D-2726 and the height of each compacted specimen was measured after extrusion.
9. The maximum theoretical specific gravity of the mix was determined in accordance with ASTM D-2041, and

the air voids were calculated in accordance with ASTM D-3203.

4.2.3 Schweyer Rheometer Test

4.2.3.1 Background

The theoretical background for the Schweyer constant stress rheometer and application of rheological concepts established by H.E. Schweyer have been presented by Tia and Ruth [89]. Major procedures for analysis of Schweyer rheometer data are summarized as follows:

1. Calculate the uncorrected shear stress using the following expression:

$$\tau' = K_\tau F \quad (4.1)$$

where

τ' = uncorrected shear stress, Pa

K_τ = $1/(2\pi DL)$ for plug flow tube with uniform diameter

K_τ = $D_c/(\pi L_c D_t^2)$ for sample tube with capillary

F = plunger force, N

2. Calculate the uncorrected shear rate using the following expression:

$$\gamma' = K_\gamma V \quad (4.2)$$

where

γ' = uncorrected shear rate, s^{-1}

$K\gamma$ = $8/D$ for plug flow tube with uniform diameter

$K\gamma$ = $8D_t^2/(D_c^3)$ for sample tube with capillary

V = velocity of flow in sample tube

3. Plot the log τ' (shear stress) versus log γ' (shear rate). The shear susceptibility factor (C) is then obtained from the slope of the logarithm shear stress versus logarithm shear rate plot. If C is 1.00, the material exhibits Newtonian flow behavior. If C is less than 1.0, the bitumen is shear susceptible and behaves as a pseudoplastic material. If C is larger than 1.0, the material is shear susceptible but possess a response to stress opposite to that of the pseudoplastic.

4. Compute the viscosity at shear rate of 1.0 sec^{-1} using both geometry (G) and Rabinowitsch (R) correction factors as follows:

$$\eta_{1.0} = (\tau' G)/(R*\gamma')^{C} \qquad (4.3)$$

where

G = $[1 + (L_t/L_c)(D_c/D_t)^{3C+1}]^{-1}$ for geometric correction factor

L_t = the mean length of sample during test

L_c = the length of capillary

D_c = diameters of capillary

D_t = diameters of sample tube

R = (0.75 + 0.25/C) for Rabinowitsch correction factor

C = shear susceptibility factor

5. Compute the apparent viscosity at a constant power input of 100 W/m^3 through the viscosity at shear

rate of 1.0 sec^{-1} using the following expression:

$$\eta_j(\text{where } j = 100 \text{ w/m}^3) = \eta_{1.0}\left(\frac{100}{\eta_{1.0}}\right)^{(c-1)/(c+1)} \qquad (4.4)$$

where

j = $\tau_j \dot{\gamma}_j$, constant power input, w/m^3

η_j = apparent viscosity at a constant power input of j

The constant power viscosity has the advantage of minimizing extrapolation errors because the shear rate ($\dot{\gamma}_j$) is within or close to the shear rates obtained from the rheometer tests. However, viscosity measurements at one temperature are usually not enough to define the low temperature rheological behavior of bitumens. It is desirable to obtain test results at different temperatures and to plot a log viscosity versus log temperature curve.

4.2.2.2 Experimental procedure

The procedures for Schweyer constant stress rheometer test consist of the following steps:

1. A sample tube is filled with asphalt blend to approximately 2 to 6 mm (0.08 to 0.24 in.) from the top of the sample tube.
2. The plunger is pushed into the sample tube.
3. The entire assembly is placed into the metal block, which is then cooled or heated to testing temperature.

4. Once the temperature has stabilized, the gas pressure is preset and the gas cyclinder is activated to apply force to the plunger and test sample.
5. The creep curve is recorded through a data acquisition system for each stress level until the response becomes linear. Usually 2 minute is enough.
6. Tests are conducted at a minimum of five stress levels, usually between 100 psi and 20 psi.
7. The shear stress versus shear rate relationship is obtained and plotted by using a computer progrem.
8. The shear susceptibility (C), viscosity at a shear rate of 1.0 sec-1 ($\eta_{1.0}$) as well as the constant power viscosity (η_i) are then obtained through the computer program.

4.2.4 Infrared Spectroscopic Test

4.2.4.1 Background

Infrared spectroscopy is an analytical method where the infrared radiation is passed through the sample and the amount of the radiation absorbed (or transmitted) by the sample is measured.

The chemical functionality in asphalt or the modifier in asphalt and the changes in themical functionality with aging are then examined by a functional group analysis. If the spectrum does not contain an absorption band typical of a certain functional group, it can be deduced that the molecules do not contain that functional group. On the other hand, molecules, which contain many different kinds of functional groups generally give poor spectra. The recorded spectrum is a plot of percent absorbed (or transmitted) versus wavenumber.

4.3.4.2 Experimental procedure

The original or aged asphalt blends are dissolved in tetrahydrofuran (THF) at a 5 percent concentration and evaluated in the FTIR spectrophotometer. The testing procedures for infrared spectral test are described as follows:

1. The asphalt blend is weighed out in an amount from 0.2 to 0.3 gram in a 3 gram glass vial. The weight is accurately measured to a hundredth of a gram.
2. HPLC grade Tetrahydrofuran (THF) is used to dissolve the asphalt blend to a 5 percent (W/V) solution. The solution in the vial is tightly stoppered and is occasionally shaken to accelerate the dissolving of asphalt blend sample. (WARNING: THF is toxic, read product data and safety sheets.)
3. The sealed cell is cleaned by using 3 cc Luer Lock syringes with THF. The cleaned sealed cell is then filled with THF. Care has to be taken to ensure that no air bubbles are entrapped.
4. The filled sealed cell is then inserted into the cell holder in the sample compartment of the spectrophotometer. Then the sample compartment is closed.

5. The system software is operated to scan the solvent to generate the background spectrum for THF. The background spectrum is stored on the disk facilities. The background spectrum is generated and saved in diskette on every occasion that the test is run.
6. The sealed cell is removed from compartment and cleaned through the use of syringe with THF, and then blown dry.
7. The sealed cell is filled with asphalt sample by using 3 cc Luer Lock syringes. Then step 4 is done again.
8. The system software is operated to scan the solvent to generate the spectrum for solution. Using software commands, the background spectrum is ratioed out and the spectrum of the asphalt blend sample is yielded, and stored on the disk facilities.
9. Using various software commands, the analysis of the spectrum of the asphalt blend was done, so as to obtain the values of absorbance at different wavenumbers.
10. The carbonyl ratios and Ketone Factors can be calculated using the values obtained in step 9.
11. A hardcopy of the spectrum is obtained on a connected plotter.

12. The sealed cell is rinsed out with THF until thoroughly clean and put away when done for the day. The sealed cell is then stored in a dry desiccated chamber.

4.2.5 Indirect Tensile Test

4.2.5.1 Background

This test is conducted by loading a cylindrical specimen along its length. This compressive loading produces a fairly uniform tensile stress perpendicular to the plane of the applied load and along the vertical diametrical plane that causes the specimen to fail by splitting along the vertical diameter. Both the horizontal and vertical deformations as well as the applied load can be measured during the test.

On the basis of the maximum failure load of P, applied through a loading strip of width 1/2 in., the tensile strength at failure S_t, can be computed with the relationship

$$S_t = (1.96P)/\pi td \tag{4.5}$$

where

S_t = Indirect tensile strength, psi

P = Ultimate vertical diametral load, lbf

t = Specimen thickness, inches

d = Specimen diameter, inches

Basically, the indirect tensile strength of asphalt mixtures can be measured at either a high loading rate (2 in./min) at a higher temperature or a low loading rate (0.05 in./min) at a lower temperature to compare the thermal-load-induced stresses to evaluate the effects of thermal variation on mixtures. Button et al. (15) performed the indirect tensile test using high loading rates and low loading rates at various cold temperatures ranging from -15°C to 25°C to evaluate the effects of loading rates on low temperature testing. The test results from their study indicated that the resistance to traffic-induced cracking was increased when the strength of the mix at a high loading rate was increased.

4.2.5.2 Experimental procedure

The procedures for the indirect tensile test are briefly described as follows:

1. The test specimens are placed in a temperature-controlled chamber at the specified test temperature for at least 24 hours to ensure that the temperature is stabilized before the test.
2. The test specimen is placed into the lateral deformation extensometer device and whole diametral device is placed on the top of 0.5-inch-wide steel loading strip and adjusted to be parallel and well centered on the vertical diametral plane. The diametral device consists of two extensometers with gauge length extenders, and two specimen adapter brackets are checked to ensure that the brackets contact the specimen all along the thickness. A small pre-load of approximately 3 percent of the maximum load is first applied to the specimen to help sitting the loading strip on the specimen.

3. A compressive load is applied at a rate of 2 inches per minute until specimen failure. The applied load and horizontal deformation are recorded through the electronic load cell and the extensometers, respectively. Both load and deformation are plotted on the chart recorder.
4. The indirect tensile strength then can be calculated by using the relationship mentioned previously. A typical indirect tensile strength test report generated by the computer software is shown in Table 4.10

4.2.6 Resilient Modulus Test

4.2.6.1 Background

The dynamic resilient modulus has been defined as the ratio of the applied stress to the recoverable strain when a repeated dynamic load is applied. Basically, the test method is conducted by applying a pulse load at relatively short time duration and recording the instantaneous deformation using strain gages or linear variable differential transformers (LVDTs). The resilient moduli are then calculated from the computed induced stresses and measured strains.

Schmidt, R.J. [90] developed a diametral method to determine the resilient modulus of a variety of polymer modified specimens. In this method, a pulsating load of 0.1 second duration is applied diametrally to the standard Marshall specimen every 3 seconds, and the corresponding

Table 4.10 Indirect tensile strength test report

```
                              Test summary

Test file :    41A01ST
General Information

     Units                                          3
     Operator's Name                                SCH
     Project Number                                 UFAGE
     Specimen Serial Number                         41F
     Specimen ID                                    A01

Specimen & Station Parameters

     Full Scale Load (lbs)                          10000
     Full Scale Displacement (in.)                  5
     Specimen Diameter (in.)                        4
     Specimen Thickness (in.)                       2.516
     Test Temperature (deg F)                       41

Control Parameters

     Displacement Rate (in./min)                    2
     Load Decrease (%)                              20
     Maximum Actuator Travel (in.)                  5

Test Results

     Test Start                                     09-15-1992
     Reason for Test Shutdown                       Load   Drop-off
     Detected
     Type of Failure                                N
     Ultimate Load (lbs)                            7451.477
     Corresponding Ultimate Stroke (in.)            5.142212E-02
     Ultimate Tensile Strength (psi)                471.359
```

horizontal deformation is measured through the mounted transducers. This diametral resilient modulus device in mix design is now standardized in ASTM D-4123 which recommends the application of compressive loads with a haversine or suitable wave form. The load is applied vertically in the vertical diametral plane of a cylindrical specimen through a loading strip of 0.5 inch width. The resulting horizontal deformation of the specimen is measured and, with an assumed Poisson's ratio, is used to calculate the resilient modulus.

The resilient moduli then can be calculated by the following expressions:

$$M_{RI} = P\ (\ \mu_{RI} + 0.27\ )\ /\ (td_{RI}) \qquad (4.6)$$

$$M_{RT} = P\ (\ \mu_{RT} + 0.27\ )\ /\ (td_{RT}) \qquad (4.7)$$

where

M_{RI} = instantaneous resilient modulus of elasticity, psi (or MPa),

M_{RT} = total resilient modulus of elasticity, psi (or MPa),

μ_{RI} = instantaneous resilient Poisson's ratio,

μ_{RT} = total resilient Poisson's ratio,

P = repeated load, lbf (or N),

t = specimen thickness, in. (or mm),

d_{RI} = instantaneous recoverable horizontal deformation, in. (or mm),

d_{RT} = total recoverable horizontal deformation, in. (or mm).

A value of 0.35 for Poisson's ratio has been found to be reasonable for asphalt mixtures at 25°C (77°F) [91], However, a value of 0.2 of poisson ratio was employed at temperature of 5°C (41°F).

This test has been used widely by many researchers for testing mixtures properties. Button et al. [15] performed the resilient modulus test on modified and unmodified mixtures at various temperatures ranging from -32°C (26°F) to 38°C (100°F) to evaluate the mixture temperature susceptibility. They reported from this test that there are not significant differences between low temperature performance of conventional asphalt and polymer modified binders. They indicated that a resilient modulus of approximately 2,000,000 psi at low temperature is the maximum value for either conventional asphalt mixes or modified asphalt mixes. However, King et al. [24] stated that polymer modified mix showed approximately 10 percent lower complex moduli at low temperature of -10°C and 17 percent higher modulus at high temperature of 40°C than that of conventional asphalt mix. Carpenter et al. [25] conducted the dynamic resilient modulus text at temperature of 4.4°C, 22°C, and 38°C (40°F, 72°F, and 100°F). They indicated that polymer-modified asphalt binders provided a stiffer asphalt concrete at elevated temperatures yet maintained a stiffness below that of base asphalt at low temperature. Krater et al. [27] performed resilient modulus test at different temperatures of -12°C, 1°C, 25°C, and 40°C

(10°F, 34°F, 77°F,and 104°F). They stated that the polymer modified mixtures show significantly better performance at high temperature testing and slightly better performance at low temperature testing.

4.2.6.2 Experimental procedure

The procedures for resilient modulus test are performed as follows:

1. The test specimens are placed in a temperature-controlled chamber at the specified test temperature for at least 24 hours to ensure that the temperature is stable before the test.
2. The test specimen is placed into the lateral deformation extensometer device and the whole diametral device is placed on top of a 0.5-inch-wide steel loading strip and adjusted to be parallel and well centered on the vertical diametral plane. The diametral device consists of two extensometers with gauge length extenders, and two specimen adapter brackets, which are checked to ensure that the brackets contact the specimen all along the specimen side. A small pre-load of approximately 3% of the maximum load is first applied to the specimen to help to sit the loading strip on the specimen and to maintain a slight load between each load cycle.
3. A pulsating haversine load of approximately 15 percent of the maximum load is applied to the

specimen at a loading frequency of 0.33, 0.5, and 1.0 Hz with a duration of 0.1 second for preconditioning the specimen.

4. Pre-conditioning of the specimen continues until the rate of deformation of the specimen is essentially constant. When preconditioning is complete, the computer software will begin taking test data, signaling the end of pre-conditioning. The specimen is cycled (loaded, unloaded) five times at the load, frequency and load duration specified by the operator. When testing at the first cycle frequency is complete, the test continues with specimen preconditioning and cycling at the next cycle frequency. This repeats through three cycle frequencies.
5. The specimen is rotated by 90 degrees and the test is repeated.
6. Applied loads and the horizontal deformations are measured through the load cell as well as the deformation extensometer system, respectively. Both load and deformation are plotted on the computer software automatically. A typical load-pulse deformation trace is shown in Figure 4-1.
7. The average recoverable horizontal deformations are measured over at least three loading cycles after the repeated resilient deformation become stable.

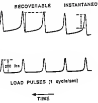


Figure 4.1 Typical load-pulse deformation trace

8 The resilient modulus was then calculated using average values obtained by using Equation 4.6 or 4.7. Table 4.11 displays a typical resilient modulus results at a cycle frequency from computer software.

4.2.7 Fracture Energy Test

The induced horizontal strain and applied vertical stress were used to establish fracture energy (F_E) values using the expression:

$$F_E = \int_0^{\epsilon_0} \sigma d\epsilon \qquad (4.8)$$

where

σ = applied vertical tensile stress, Pa

ϵ = induced horizontal strain

ϵ_0 = failure strain

Applied stress was calculated for each value of the load using Equation 4.4. Using the corresponding value of horizontal deformation, the elastic modulus was calculated using Equation 4.7. Poisson's ratio was assumed as 0.35 for temperature of 25°C (77°F) and 0.2 for temperature of 5°C (41°F) [92]

Using the calculated values of applied stress and elastic modulus, the induced strain was obtained by the relation

$$\epsilon = \sigma/E \qquad (4.9)$$

Thus, for each specimen tested, ten data points were used to define the relationship between applied vertical stress and induced horizontal strain. The area under this curvilinear relationship was calculated using the trapezoidal rule, which yielded the value of fracture energy.

Table 4.13 Instantaneous and total resilient modulus for selected asphalt mixture

Asphalt Resilient Modulus Test

Test File : UFAGE\41AG02
Specimen SN : 41F
Project Number . UFAGE

Cycle Frequency : 0.5 Hz
Load Duration : 0.1 sec

Rotation : 0 Degrees

Test Cycle	Instantaneous Values Resilient Modulus psi	 Poisson's Ratio	Total Values Resilient Modulus psi	 Poisson's Ratio
1	2192876	0.200E+00	1734235	0.200E+00
2	2252726	0.200E+00	1737397	0.200E+00
3	2088616	0.200E+00	1700347	0.200E+00
4	2193414	0.200E+00	1734660	0.200E+00
5	2305147	0.200E+00	1670138	0.200E+00

Rotation : 90 Degrees

Test Cycle	Resilient Modulus psi	Poisson's Ratio	Resilient Modulus psi	Poisson's Ratio
1	2127318	0.200E+00	1726719	0.200E+00
2	2144623	0.200E+00	1738126	0.200E+00
3	2111468	0.200E+00	1642253	0.200E+00
4	2061643	0.200E+00	1693961	0.200E+00
5	2045856	0.200E+00	1704880	0.200E+00

4.3 Equipment and Facilities

This section describes the equipment used in this study. They include a mixer which was used to blend the asphalt with modifiers, a forced-draft oven which was used to provide the aging condition for asphalt specimens, and the testing equipment utilized for the strength, rheology and infrared spectral tests.

4.3.1 Variable-speed Mixer

A mixer with a variable-speed propeller was used to blend the asphalt and modifiers in a quarter-pint aluminum can, which was heated directly by an electric heating plate where the temperature is adjustable. A conventional thermometer was immersed in the mixture to monitor the temperature.

4.3.2 Forced Draft Oven

A standard laboratory oven was modified to enable air flow through the oven. This was done by providing a large inlet port on one side of the oven and a small exit port on the top of the oven. These two ports were connected externally by flexible aluminum air duct. A 375 cfm air booster was placed external to the oven, in the duct line, adjacent to the inlet port to provide the circulation of the air in the oven. The oven temperature was maintained at 60°C (140°F) with the help of thermostat switch and sensor. Figure 4.2 depicts the forced draft oven.

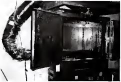


Figure 4.2 Picture of forced-draft oven

4.3.3 MTS Closed Loop Hydraulic Testing System

The resilient modulus, indirect tensile and fracture energy tests were performed by using the MTS closed loop servo-hydraulically controlled loading system. The machine consists mainly of a control unit, load frame, load cell, servo-hydraulically controlled actuator, an environmental chamber, a resilient modulus fixture, control electronics, deformation measurement transducers, and testing software, which are shown in Figure 4.3. Figure 4.4 illustrates the picture of servo-hydraulically controlled actuator, temperature controllor.

Two load cells with maximum capacity of 2000 lb and 1000 lb were used for load measurements. The vertical displacement are measured by using an axial extensometer which was mounted on the top loading strip. Horizontal displacements are measured through a diametral device as shown in Figure 4.5. The diametral device consists of two extensometers with gauge length extenders, and two specimen adapter brackets. The brackets are machined to the same radius as the specimen and are in contact with the specimen along the side of the specimen. In this way, each bracket records the maximum lateral extension that occurs on each side of the specimen. Two 1/2-inch wide stainless steel loading strips were used to apply the load to the specimen as shown in Figure 4.6 The loading strips were curved at the interface with the specimen with a radius of 2 inch. Two guide rods were used to prevent any eccentricity in loading.

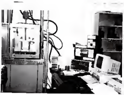


Figure 4.3 Picture of MTS machine

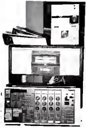


Figure 4.4 Picture of servo-hydraulically controlled actuator and temperature controller

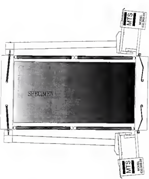


Figure 4.5 Diametral device for the measurment of horizontal deformation

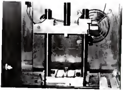


Figure 4.6 Picture of loading arrangement

4.3.4 Constant Stress Rheometer

A Cannon Schweyer Constant Stress Rheometer was used to measure the rheological properties of asphalt blends at lower temperature such as 25°C (77°F) and lower. Figure 4.7 shows the rheometer. A schematic of the test set-up is shown in Figure 4.8. The apparatus consists of a nitrogen gas operated pneumatic cylinder which applied a specific force to the plunger and force the sample through the capillary. Movement of the plunger was measured by a LVDT and recorded as a function of time. The output voltage was digitized and acquired by a data acquisition system. The data system was operated on a IBM PC-compatible computer.

The sample tube is inserted into an insulated aluminum block where the temperature is cooled or heated to the desired testing temperature through the refrigeration unit with the combination of an electrical wire heater.

4.3.5 Infrared Spectrophotometer

4.3.5.1 Fourier transform infrared spectroscopy

An optical system which uses an interferometer and a dedicated computer are two major parts in the Fourier Transform Infrared (FTIR) spectrometer. The computer controls the optical components, collects and stores data, performs computations on data and displays the needed spectra. The use of interferometer in an FTIR spectrophotometer overcomes the major disadvantage of conventional spectrophotometer where the grating and prism is used.

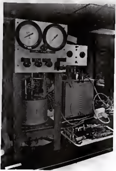


Figure 4.7 Picture of Cannon Schweyer rheometer

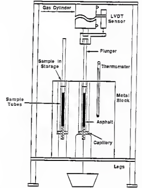


Figure 4.9 Schematic of Cannon Schweyer rheometer

The major distinction between FTIR spectrometer and conventional spectrometer is in the design of the interferometer and the way in which the interferometer is operated. The interferometer may be operated by scanning in a discontinuous, step-wise manner (step scan inteferometer), a slow continuous manner with chopping of the infrared beam (slow scanning), or rapidly without chopping of the infrared beam. The rapid scanning Fourier transform spectrophotometer with a Michelson interferometer, which was named after the inventor, have resulted in the widespread application of the IR spectroscopy to chemical analysis problems.

The fact that higher signal-to-noise ratios for spectra obtained under conditions of equal measurement time accounts for the principal advantage of the use of Fourier transform infrared spectroscopy with Michelson interferometer. The signal-to-noise advantage is a result both of the concurrent measurement of the detector signal for all resolution elements of the spectrum and of the high optical throughput of the FTIR spectrophotometer. Throughput is usually defined as the product of the area and solid angle of the beam accepted by the instrument.

One other basic advantage in the use of the Michelson interferometer for spectrophotometer is the higher accuracy in frequency for spectra taken over a wide range of frequencies.

4.3.5.2 Testing system

The infrared spectroscopy tests were run on the Perkin-Elmer Model 1600 Fourier Transform Infrared Spectrophotometer. The spectrophotometer is a bench-top instrument consisting of an electronics system based on the Motorola 68010 Central Processing Unit, a single-beam purgeable sample compartment, a dedicated keyboard for controlling the instrument and interacting with the software. The system offers a resolution of 2 cm^{-1} throughout the standard range of 7800 to 100 cm^{-1}. Figure 4.9 illustrates the system which was used. Figure 4.10 shows the sealed cell, vial and syringe.

Figure 4-9 Picture of FTIR system used

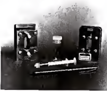


Figure 4.10 Picture of sealed cell, vial and syringe

CHAPTER 5
EFFECTS OF MODIFIERS ON TEMPERATURE SUSCEPTIBILITY AND AGING CHARACTERISTICS

5.1 Introduction

A laboratory investigation was performed to evaluate the effects of selected promising modifiers on the temperature susceptibility and short-term aging characteristics of typical asphalt cements. The high-temperature and low-temperature potential performance of the modified asphalts were also assessed from the laboratory results. The detail laboratory program is presented in chapter 3.

5.2 Effect of Modifiers on Temperature Susceptibility

The temperature susceptibility of a paving asphalt has been defined as the change in consistency (penetration or viscosity) of the asphalt for a given change in temperature. This parameter is very important in characterizing potential performance of paving asphalts. A high temperature susceptibility would usually result in poor performance of the asphalt as its consistency varies too much over the anticipated temperature changes. Several methods have been employed for representing the temperature susceptibility of asphalts. Three of these methods are applied in the analysis of the data and are discussed below. The first method presented is an empirical plot of log viscosity as a function of temperature and the second is penetration viscosity number (PVN). Bitumen Test Data Chart (BTDC) will be used as the third alternative.

5.2.1 Viscosity Temperature Susceptibility

The viscosities of the original unmodified asphalts at the various different temperatures were plotted in accordance with ASTM D2493 to evaluate the temperature susceptibility of these materials. Linear regression analysis was performed to determine a best-fitted line to relate viscosity to temperature for each binder evaluated in the study. The regression equation used was of the following form:

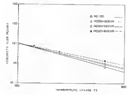
$$\mathrm{LogLog}\ (\eta) = A + B\ \mathrm{Log}\ (T) \qquad (5.1)$$

where

η = viscosity in poises or stokes

T = absolute temperature in °R

A more negative slope would indicate a higher temperature susceptibility. Figure 5.1 shows the plots of viscosities verus temperatures for the original unmodified AC-20 and the EVA modified AC-20 asphalts. Figure 5.2 shows similar plots for the original unmodified AC-30 and AC-30 modified with different amounts of GTR-80. Appendixes B-1 illustrate similar plots for the rest of different modified asphalts. As seen from the slopes of the viscosity-temperature plots, all of the modifiers studied demonstrated the ability to



Regression Equation

AC-20: LogLog(Vis)= 19.507 - 6.997Log(Temp) R^2= 0.9921

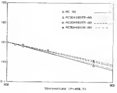
AC-20+ 3% EVA: LogLog(Vis)= 17.661 - 6.244Log(Temp) R^2= 0.9976

AC-20+ 5% EVA: LogLog(Vis)= 17.346 - 6.051Log(Temp) R^2= 0.9979

AC-20+ 6% EVA: LogLog(Vis)= 15.083 - 5.2151Log(Temp) R^2= 0.9951

Note: Viscosity in Poise
Temperature in °F+459.7

Figure 5-1 Relationship Between Viscosity and Temperature for EVA Modified AC-20s.



Regression Equation

AC-30:	LogLog(Vis)= 19.898 - **6.923**Log(Temp)	R^2= 0.9912
AC-30+ 2% GTR80:	LogLog(Vis)= 18.918 - **6.596**Log(Temp)	R^2= 0.9999
AC-30+ 5% GTR80:	LogLog(Vis)= 17.032 - **5.933**Log(Temp)	R^2= 0.9959
AC-30+ 8% GTR80:	LogLog(Vis)= 15.847 - **5.499**Log(Temp)	R^2= 0.9959

Note: Viscosity in Poise
Temperature in °F+459.7

Figure 5.2 Relationship Between Viscosity and Temperature for GTR-80 Modified Asphalts.

substantially alter the temperature susceptibility of the asphalt cements. The degree of alteration is highly dependent on the type of modifiers and the chemical composition of the asphalt cement. Generally, the higher the modifier concentration, the lower the temperature susceptibility would be. Basically, AC-30 asphalt with 10 percent carbon black has a similar temperature susceptibility to that of AC-30 asphalt with 5 percent gilsonite and AC-30 asphalt with 2 percent GTR-80 for the temperature range of 5°C (41°F) to 135°C (275°F). Based on the viscosity temperature susceptibility from 5°C (41°F) to 135°C (275°F), the addition of 5 percent carbon black to the AC-30 control asphalt showed the least influence on temperature susceptibility among all the modifiers studied.

5.2.2 Penetration Viscosity Number (PVN)

Pen-Vis number (PVN) is based on the penetration at 25°C (77°F) and the corresponding viscosity at 135°C (275°F) of paving asphalts [53]. It is a means of evaluating the temperature susceptibility of asphalts. It is defined by the following equation:

$$PVN = \frac{[(4.26800-0.79670LogP)-(LogV)]}{[(4.25800-0.79670LogP)-(3.46289-0.61094LogP)]}(-1.5)$$

where

V = kinematic viscosity in centistokes measured at 135°C

P = Penetration at 25 °C (77 °F)

A high value of PVN would indicate a material that has a low temperature susceptibility. Appendix B-2 shows the penetration at 25°C (77°F) and viscosity at 135°C (275°F) and the corresponding pen-vis number. The PVN values after aging by TFOT at 163°C (325°F) are also shown. Figure 5.3 displays the pen-vis number of different original modified asphalts.

All of modified asphalts showed a significant higher PVN as compared with the unmodified asphalts. Coarse tire rubber increased the PVN the most, and carbon black increased the PVN the least. After TFOT aging, a few modified binders showed an increase in PVN while other modified binders showed a reduction in PVN. No clear trends on the effects of aging on the PVN of modified asphalts could be observed. Generally, according to Mcleod's criteria, the asphalt used in this study is suitable only for moderate-volume traffic. However, after the modifiers modification, even the least improved modified asphalt (with an PVN of -0.49) still would be suitable for a high-volume traffic condition.

5.2.3 Bitumen Test Data Chart (BTDC)

The viscosities and penetrations of the original unmodified and modified asphalts at the various different temperatures were plotted on Bitumen Test Data Charts (BTDC) to evaluate the temperature susceptibility of the modified asphalts. Figure 5.4 shows the BTDC plots of the unmodified AC-30 asphalts in comparison with the different amounts of GTR-80 modified AC-30 asphalts. As seen from the slopes of the

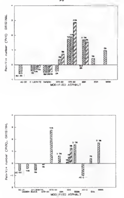


Figure 5.3 Pen-vis numbers of modified asphalts

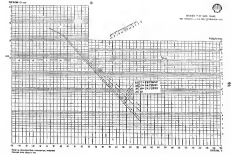


Figure 5.4 Viscosity and penetration vs. temperature for conventional asphalt compared to different modified asphalts

BTDC plots, the temperature susceptibilities of the modified asphalts are generally lower than that of the unmodified asphalt. The BTDC plots of the other different modified asphalts are shown in Appendix B-3.

5.3 Effects of Modifiers on High Temperature Characteristics

Both absolute and kinematic viscosities were measured in accordance with ASTM D2171 and D2170 procedures at temperatures of 60°C (140°F) and 135°C (275°F), respectively. The test results are displayed in Appendix B-4. The influence of aging by the thin film oven test (TFOT) at temperature of 325°F on the absolute and kinematic viscosities are also shown. The absolute viscosity of the TFOT residue at 60°C (140°F) would represent the viscosity of the binder of a newly placed hot-mix at a typical high pavement service temperature. A higher viscosity at this temperature would mean a higher resistance to shoving and/or rutting of the mixture. It can be seen that all the modifiers substantially increase the absolute viscosities of the TFOT residues measured at 60°C (140°F), and that this effect increases as the amount of addition increases. As seen from Table B 4, SEBS influenced the absolute viscosity of AC-30 asphalt the most when compared with the other modifiers. The absolute viscosity of AC-30 + 5% SEBS is about twenty-five times greater than that of the unmodified AC-30 asphalt. It is obvious that the absolute viscosity of SEBS modified AC-30 is well out of the acceptable range for AC-30 grade asphalt.

Problems occurred when conventional viscosity measurements were made on the coarse ground tire rubber modified binders at 135°C (275°F). In some case, the Cannon capillary tubes were clogged during the test, resulting in erroneous results. Therefore, a straight walled cylinder rotational viscometer was used to measure the viscosity at the temperature of 135°C (275°F). The test results are also shown in Appendix B.4.

According to the Asphalt Institute, the optimum mixing temperature of asphalt concrete mixtures should be at a viscosity of 1.7 ± 0.2 poise. All of the modifiers used in this study produce a significant increase in the 135°C (275°F) viscosity of the original asphalt. Even when a softer grade of asphalt such as AC-5 is used with the modifiers, the 135°C (275°F) viscosity of the blend is still greater than that of the usual grade asphalt. The optimum mixing temperatures for the different binders to be used in the asphalt mixtures as determined from the BTDC plots vary from 154°C to 210°C (310°F to 410°F), which are substantially higher than that for a conventional asphalt. In order to reduce the variation of mixing temperatures used in this study, only three different mixing temperatures, namely, 149°C, 166°C , and 191°C (300°, 330° and 375 °F) were used.

5.4 Effects of Modifiers on Low-Temperature Characteristics

The effects of modifiers on low-temperature performance of the binders were evaluated by means of penetration and viscosities at low temperatures. Constant power viscosities at low temperatures of 5°C (41°F) and 25°C (77°F) of the typical asphalt cements with different amounts of different types of modifiers are given in Appendix B.5. The effects of aging by means of the thin film oven test (TFOT) at temperature of 163°C (325°F) on these two low-temperature viscosities are shown in Appendix B.6.

Statistical method ANOVA was used to analyze the constant power viscosity of the original modified asphalts at temperatures of 5° and 25°C (41° and 77°F). A one-factor fixed-effect model was used to evaluate the difference between the different asphalt blends. The statistical model used is as follows.

$$Y_{ij} = \mu + A_i + \epsilon_{ij}$$

where

i = $1, 2, \ldots, 31$

j = $1, 2$

Y_{ij} = the responses of j^{th} replicate of i^{th} asphalt

μ = overall mean

A_i = main effect of i^{th} asphalt blend

ϵ_{ij} = experimental error

Since the test data did not meet the assumption of homogeneity of variance as assumed by the ANOVA model, the data had to be transformed such that the transformed data would meet the requirement of homogeneity of variance. ANOVA was performed on the logarithms of the test data, which met the requirement of homogeneity of variance. The results of ANOVA indicated that the effect of type of asphalt blends on the constant power viscosity at 5°C (41°F) is significant at an a level of 5 percent. Subsequently, a Duncan's Multiple Range test was applied to compare the means for different types of asphalt blends. Table 5.1 shows the Duncan's grouping of the original modified asphalts on the basis of logarithm of constant power viscosity at 5°C (41°F). The test results indicated that gilsonite showed the most influence among all the modifiers on the constant power viscosity of AC-30, whereas the Carbon black influenced the constant power viscosity at 5°C (41°F) of AC-30 and AC-20 the least. Table 5.2 shows the Duncan's grouping of the original modified asphalts on the basis of logarithm of constant power viscosity at 25°C (77°F). All of the modified asphalts increased the constant power viscosity of AC-30 and AC-20 at 25°C (77°F). Carbon black influenced the constant power viscosity of AC-20 and AC-30 at 25°C (77°F) the least. SEBS influenced the constant power viscosity of AC-20 and AC-5 asphalts at 25°C (77°F) the most. It can be seen that the modifier SEBS increased the constant power viscosity at 25°C (77°F) of both the AC-20 and AC-5 asphalts by several folds.

Table 5.1 Duncan's grouping of original modified asphalts on the basis of logarithm of constant power viscosity at 5°C

```
Duncan Grouping              Mean       ASPHALT

              A              9.402     A—AC-30+5% Gilsonite
     B        A              9.293       AC-30+9% SEBS          B
     B        A              9.253       AC-30+15% Gilsonite
     B        C              9.097     C—AC-30+10% Gilsonite
     B        C    D         9.021   D   AC-30+9% EVA
     E        C    D         8.845       AC-20+3.5% SEBS        E
     E        F    D         8.779     F—AC-20+15% GTR-40
     E        F    D         8.759       AC-20+9% GRT-80
     E        F    G         8.681    G  AC-30+5% GTR-80
     E    H   F    G         8.671       AC-30                  H
     E    H   F    G         8.671       AC-20+5% EVA
     E    H   F    G         8.646       AC-20+8% EVA
I         H   F    G         8.619       AC-20+3.5% SBR         I
I    E    H   F    G J       8.961  J    AC-30+15% Carbon Black
I    E    H   F    G J       8.597       AC-20+9% Gilsonite
I    K    H   F    G J       8.511       AC-5+3.5% SEBS         K
I    K    H   L    G J       8.493     L—AC-30+8% GTR-80
I    K    H   L    G J       8.406       AC-20
I    K    H   L    M J       8.369    M  AC-30+2% SBR
I    K        L    M J       8.327       AC-30+9% Carbon Black
I    K        L    M J       8.319       AC-30+5% SBR
     K        L    M J       8.312       AC-30+20% GTR-40
     K        L    M J       8.301       AC-20+10% Carbon Black
     K        L    M         8.241       AC-30+19% GTR-40
     K        L    M         8.217       AC-30+2% GTR-80
              L    M         8.202       AC-20+3% EVA
              L    M         8.190       AC-30+3.9% SBR
              L    M         8.189       AC-30+10% GTR-40
              L    M         8.199       AC-30+10% Carbon Black
                   M         8.392       AC-5+5% EVA
              N              7.979   B   AC-5
```

Note:means with the same letter are not significantly different
(alpha=0.05)

Results of ANOVA

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
ASPHALT	30	9.31448327	0.31048278	19.16	0.0001

R-Square = 0.94883

Table 5.2 Duncan's grouping of original modified asphalts on the basis of logarithm of constant power viscosity at 25°C

Duncan Grouping				Mean	ASPHALT
		A		7.1927	A—AC-30+20% GTR-40
B		A		7.0046	AC-30+15% GTR-40—B
B				6.5542	AC-30+15% Gilsonite
B		C		6.8225	C—AC-20+3.5% SEBS
B		C		6.8035	AC-30+5% SEBS
		C		6.7335	AC-30+10% Gilsonite
		D		6.4824	D—AC-20+8% EVA
E		D		6.3657	AC-20+15% GTR-40—E
E		F		6.2190	F—AC-20+5% Gilsonite
E		F		6.2045	AC-30+8% GTR-80
E		F		6.1815	AC-20+5% EVA
G		F		6.0881	AC-30+5% GTR-80—G
G		F	H	6.0480	H—AC-5+3.5% SEBS
G		F	H	6.0447	AC-30+10% GTR-40
G		I	H	5.5447	I—AC-20
G		I	H	5.5371	AC-20+3.5% SBR
J		I	H	5.8584	AC-30+5% Gilsonite—J
J		I		5.8242	AC-20+5% GTR-80
J		I		5.8035	AC-20+3% EVA
J		I	K	5.7833	K—AC-30+5% EVA
J		I	K	5.7701	AC-30+3.5% SBR
J	L	I	K	5.7534	AC-30+10% Carbon Black—L
J	L	M	K	5.7103	M—AC-30+2% GTR-80
N	L	M	K	5.5805	AC-30+15% Carbon Black—N
N	L	M		5.5578	AC-30+2% SBR
N		M		5.5321	AC-20+10% Carbon Black
N		M		5.5303	AC-30+5% Carbon Black
N				5.4183	AC-10+5% SBR
		O		5.2227	O—AC-10
		O		5.1328	AC-5
		O		5.1170	AC-5+5% EVA

Note: means with the same letter are not significantly different
(alpha=0.05)

Results of ANOVA

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
ASPHALT	30	18.5578217	0.61550072	74.77	0.0001

R-Square = 0.9864

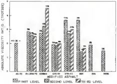
Penetration along with penetration ratio of all asphalt blends at both 4°C (39.2°F) and 25°C (77°F) are presented in Appendix B.7. The influence of aging by the thin film oven test (TFOT) at temperature of 163°C (325°F) on penetration are also shown.

Additions of 5 percent and 10 percent of carbon black influenced the penetration the least at both 4°C (39.2°F) and 25°C (77°F). All modifiers decreased the penetration at 25°C (77°F). All of the modifiers showed no significant influence on the low temperature penetration.

5.5 Effects of Modifiers on Aging Characteristics

5.5.1 Viscosity Ratio and Percent Penetration Retained

The effect of asphalt aging is often expressed by means of aging index. The aging index is defined as the ratio of the viscosities after aging to the viscosities before aging. It is a measure of structuring from age hardening which is caused by a combination of oxidation and the increase in the molecular interactions. Viscosity ratio at temperatures of 60°C, 135°C, and percent penetration retained at 25°C (77°F) are displayed in Figures 5.5 through 5.7. As seen from these figures, the control AC-30 asphalt modifed with fine ground tire rubber, thermoplastic block copolymer SEBS and thermoplastic polymer EVA are slightly less susceptible to age hardening than those of carbon black modified, gilsonite modified and unmodified AC-30 asphalts. Among all the modifiers evaluated, the



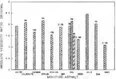


Figure 5.5 Absolute viscosity ratio vs. modified asphalts

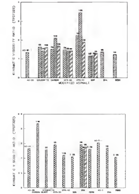
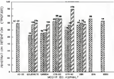


Figure 5.6 Kinematic viscosity ratio vs. modified asphalts



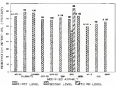


Figure 5.7 Percent penetration retained of modified asphalts

thermoplastic block copolymer SEBS reduced the aging index of the AC-30 the most. The aging index of the AC-5 + 3.5% SEBS polymer is significantly lower than that of the unmodified AC-30 or the AC-20 control asphalts. This indicated that the addition of thermoplastic block copolymer to asphaltic binder significantly improved the durability of the asphalt.

Basically, modifiers can influence the aging characteristics by various mechanisms. They may restrict the oxidation or undergo oxidation through the catalytic effect. For example, the asphalt modified with fine ground tire rubber significantly lowered the aging index. It is believed that the antioxidants in the rubber is the cause for the decrease of the aging index.

5.5.2 Infrared Spectroscopy

Infrared Spectral analyses were performed on all modified and unmodified asphalts before and after aging. Recent research done at the University of Florida [85,87] on the use of infrared techniques indicated that as the level of oxidation increase, the carbonyl absorption in the 1700 cm^{-1} region increases. This is due to increasing concentration of ketones and anhydrides. Also, carbonyl absorption of acid types occurs at about 1730 cm^{-1}. Basically, ketones, sulfoxides and anhydrides are formed on oxidative aging and carboxylic acids occur naturally in the asphalt but increase on oxidative aging. Ketones and sulfoxides are the major oxygen-containing functionalities produced in asphalts during oxidative aging.

Ketones are not naturally occurring in petroleum but are easily formed upon exposure to atmospheric oxygen and are very unstable at high temperatures. Since these four functional groups are the most significant chemical functionalities which can be related to oxidative aging, examination of the infrared spectra of the asphalt blends before and after aging were done with particular reference to them. Study of the spectra from unmodified asphalts and modified asphalts indicated that the aging mechanism of the asphalt was not significantly altered by the presence of the modifiers (see Figure 5.8). Therefore, the carbonyl ratio, which is the ratio of absorbance at 1700 cm^{-1} and 1600 cm^{-1}, and which has been used to express the level of oxidation for asphalt, can also be used to evaluate the oxidation of modified asphalts. The EVA resin concentration was monitored by following the peak intensity of the carbonyl band of its acetate functionality, which occurs at about 1736 cm^{-1} (see Figure 5.9). Comparison of the acetate band peak intensities of the aged and unaged EVA modified asphalts (see Figure 5.10) showed that absorbance at wavenumber of 1736.8 cm-1 decreased from 0.5057 to 0.3907 after aging. However, this difference was automatically canceled in the calculation of carbonyl ratio. The results of the infrared spectroscopy on the original and aged modified asphalts and unmodified asphalts are shown in Appendix B.8.

ANOVA was performed on the results of the infrared spectroscopic analyses on original and aged modified asphalts.

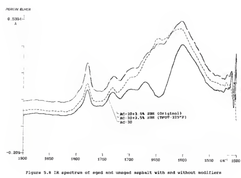


Figure 5.8 IR spectrum of aged and unaged asphalt with and without modifiers

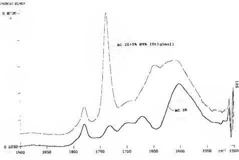


Figure 5.9 IR spectrum of unaged asphalt with and without modifiers

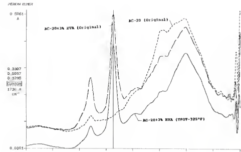


Figure 5.10 IR spectrum of aged and unaged asphalt with and without modifiers

The results of ANOVA on the carbonyl ratios of the original and aged modified asphalts indicated that the effect of the type of asphalt blends on carbonyl ratio is significant at an a level of 5 percent. The Duncan's grouping of the original and aged modified asphalts on the basis of carbonyl ratio are shown in Tables 5-3 and 5-4, respectively. It is seen that SEBS block copolymer has the least influence on the carbonyl ratio of the modified asphalts, while elastomeric polymer SBR showed the most influence among all the modifiers.

5.6 Summary of Findings

Based on the results of these tests on asphalt blends, the major findings are summarized as follows:

1. The properties of an asphalt binder can be improved by addition of gilsonite, carbon black, and polymers modifiers. The degree of improvement is dependent on the types of modifiers and amount of modifiers used.
2. The temperature susceptibility of the modified asphalts was significantly lower than the conventional asphalt as evaluated by the viscosity-temperature susceptibility (VTS), penetration viscosity number (PVN), and Bitumen Test Data Chart (BTDC) plots.
3. The required mixing temperatures for modified asphalts mixtures are generally higher than that of conventional asphalt mixtures on the basis of viscosity measurements.

Table 5.3 Duncan's grouping for infrared spectroscope test on original modified asphalts

DUNCAN GROUPING		MEAN		ASPHALT
	A	0.41388	A	AC-30+5% EVA
B	A	0.40642	B	AC-30+3.5% SBR
B		0.40508		AC-20+5% EVA
B		0.40258		AC-30+2% SBR
B		0.40181		AC-20+8% EVA
	C	0.38865	C	AC-30+15% Gilsonite
D	C	0.38648	D	AC-30+10% Gilsonite
D	C	0.38512		AC-30+5% Gilsonite
D	C	0.38213		AC-30+5% SBR
D		0.37902		AC-30+15% GTR-40
	E	0.36636	E	AC-30
	F	0.35488	F	AC-30+10% GTR-40
G	F	0.35312	G	AC-5+5% EVA
G	F	0.35051		AC-20+3% EVA
G	F	0.34989		AC-20+5% GTR-80
G	F	0.34724		AC-20+3.5% SBR
G		0.34511		C-20+15% GTR-40
	H	0.33376	H	AC-30+8% GTR-80
	H	0.33317		AC-30+20% GTR-40
	I	0.31380	I	AC-30+2% GTR-80
	I	0.30581		AC-30+5% GTR-80
	J	0.29781	J	AC-5+3.5% SEBS
	K	0.28546	K	AC-20+5% Gilsonite
	K	0.28386		AC-30+5% SEBS
	K	0.28305		AC-20+3.5% SEBS
	L	0.26621	L	AC-5
	L	0.26440		AC-20

Note: Means with the same letter are not significantly different (alpha=0.05)

Results of ANOVA

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
ASPHALT	26	0.1114968	0.0042883	284.89	0.0001

R-Square = 0.98637

Table 5.4 Duncan's grouping for infrared spectroscope test on aged(TFOT 325°F) modified asphalts.

Duncan Grouping			Mean	ASPHALT
	A		0.46650	AC-20+3.5% SBR
B	A		0.45376	AC-20+5% EVA
B	C		0.44863	AC-20+8% EVA
B	C		0.44168	AC-30+15% Gilsonite
B	C		0.44131	AC-30+5% EVA
B	C		0.43928	AC-30+10% GTR-40
B	C		0.43669	AC-20+15% GTR-40
	C		0.43486	AC-30+10% Gilsonite
	D		0.41815	AC-30+3.5% SBR
	D		0.41792	AC-30+2% SBR
	D		0.41731	AC-30+5% Gilsonite
	D		0.41344	AC-30
E	D		0.41178	AC-30+15% GTR-40
E	D		0.41024	AC-30+2% GTR-80
E	D		0.40924	AC-30+8% GTR-80
E	D		0.40453	AC-20+5% GTR-80
E	D	F	0.40123	AC-30+20% GTR-40
E	G	F	0.39465	AC-30+5% SBR
H	G	F	0.38760	AC-30+5% GTR-80
H	G		0.37901	AC-20+3% EVA
H			0.37291	AC-5+5% EVA
	I		0.34037	AC-5
	I		0.33374	AC-20+5% Gilsonite
	I		0.33167	AC-20+3.5% SEBS
	I		0.32542	AC-30+5% SEBS
	I		0.32502	AC-20
	J		0.30502	AC-5+3.5% SEBS

Note: with the same letter are not significantly different.

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	26	0.1056628	0.0040640	71.08	0.0001

R-Square = 0.9856

4. Based on the results of infrared spectroscopy test, viscosity ratios and percent penetration retained, none of the modifiers greatly effected the oxidation potential of the asphalts with the exception of SBR which showed evidence of increased reactivity with oxygen.
5. Standard kinematic viscosity test by means of Cannon capillary tubes are unsuitable for asphalts modified with coarse ground tire rubber as this material will cause the clogging of the tubes. A straight walled cylinder rotational viscometer was found to be suitable for this purpose.
6. The addition of 3.5% thermoplastic block copolymer SEBS to AC-5 control asphalt binder appears to impart desirable low and high temperature properties to the original asphalt.
7. The AC-5 + 3.5% SEBS showed the lowest aging index based on absolute, kinematic viscosity and infrared spectroscopy tests when compared with all of the modified asphalts.
8. The addition of 5% GTR-80 to AC-30 control asphalt produced the highest percent penetration retained when compared with other modified asphalts.
9. The addition of 3.5% of SBR to the AC-30 control asphalt produced the highest percent penetration retained, lowest aging index, and adequately reduced

temperature susceptibility when compared with those modified with 2% and 5% of SBR.

10. The addition of 8% EVA to the AC-20 control asphalt resulted in the highest PVN value, highest penetration retained, lowest absolute viscosity ratio, lowest temperature susceptibility and increased absolute viscosity at 140°F by a factor of two when compared with those modified with 3% and 5% EVA.
11. Asphalts of the same grade modified with different types of modifiers can have very different rheological properties at either low or high temperature.

CHAPTER 6
EFFECTS OF TFOT AND RTFOT ON MODIFIED ASPHALTS

6.1 Introduction

Due to the limited experience with modified asphalt binders, long-term performance data are lacking. One concern about these materials is the durability.

The Thin Film Oven Test (TFOT) and Rolling Thin Film Oven Test (RTFOT) were conducted at elevated temperatures to evaluate the long-term performance of these binders and also to identify the optimum usage of these new asphalt blends. Although recent research done by the Strategic Highway Research Progres (SHRP) Asphalt Research [83] appears to show that thin film accelerated aging test (TFAAT), modified RTFOT, and POV combined with TFOT might provide better indicators of the aging characteristics of asphalts, these conventional tests are still important because they provide conveniently obtained information which could be used in selecting modifiers for different asphalts. The appropriateness of using the TFOT and RTFOT for simulation of the long-term aging process was also investigated.

The detail experimental program has been previously presented in Chapter 3.

6.2 Analysis Methods

Statistical analysis using the ANOVA technique was used to determine whether the effects of main factors and interactions of factors were significant.

The effects of asphalt blend type, oven type, and oven temperature were studied by means of this design. The test results from the binder tests were analyzed as results of a factorial experiment consisting of nine types of asphalt blends, three levels of temperature, and two types of ovens. In this study, the concern is only for these nine asphalt blends, three temperatures, and two types of ovens. Therefore, asphalt, temperature, and oven types are regarded as fixed effects.

The following linear model is assumed for any single measurement in the experiment:

$$Y_{ijk} = \mu + A_i + O_j + T_k + (AO)_{ij} + (AT)_{ik} + (OT)_{jk} + \varepsilon_{ijk}$$

where

i = 1,2,...,9

j = 1,2

k = 1,2,3

Y_{ijk} = response of i^{th} asphalt, j^{th} oven, and k^{th} temperature

μ = overall mean

A_i = main effect of i^{th} asphalt blend

O_j = main effect of j^{th} oven

T_k = main effect of kth oven temperature

$(AO)_{ij}$ = effect of the interaction of the ith asphalt and jth oven

$(AT)_{ik}$ = effect of the interaction of the ith asphalt and kth temperature

$(OT)_{jk}$ = effect of the interaction of the jth oven and kth temperature

e_{ijk} = experimental error

SAS/STAT computer software was used to perform the analysis. A probability of error (a) of 0.5 was used. Comparison of means were done by Duncan's multiple-range test at a significance level of 0.05.

6.3 Aging Characteristics as Observed from the Penetration-Viscosity Plots

One method of characterizing the changes in properties of an asphalt binder as it ages is to plot the relationship between penetration (at 25 °C) and absolute viscosity (at 60 °C) as the binder ages [78]. This method was used to investigate whether the laboratory-aged binders had similar characteristics as the field-aged binders. Data from previous research study [85,86,87] were used in this analysis. In the previous study, an AC-20 has been used as a binder in an actual paving project in Florida. The same asphalt has been sampled and processed by the TFOT and RTFOT at different temperatures. Figure 6.1 shows the pen-vis plots of the binders which had been aged by the TFOT and RTFOT at different

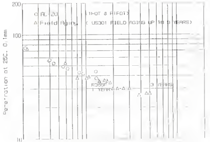


Figure 6.1 Pen-vis relationship for a selected asphalt cement at different long-term aging conditions

temperatures along with those which had been recovered from the cored samples at different ages. It can be seen that the laboratory aged binders have similar characteristics as the field-aged binders since they all fall on the same curve. A nonlinear model was used to determine a best-fitted curve to characterize the penetration- viscosity relationship over the long-term aging domain. The equation used was of the following form:

$$\mathrm{Log(pen.)} = B*e^{(C*\mathrm{Log(vis.)})} \qquad (6.1)$$

where

pen. = penetration at 25 °C (77 °F), 0.1mm

vis. = viscosity at 60 °C (140 °F), poise

Results of regression analyses show that the exponent C is approximately equal to -0.20. As seen from Figure 6.1, it appears to be appropriate to use a high process temperature to simulate long-term aging in the field, since the characteristics of the aged binders are similar to one another. It was observed that the RTFOT aging process performed at temperature of 185 °C (365 °F) can simulate a one-year field aging under typical Florida conditions. The same nonlinear model was used to curve-fit the pen-vis relationship for the modified asphalts, which are shown in Figure 6.2. As seen from Figure 6.2, the aging trend of the fine ground tire rubber modified asphalt is similar to that of the SBR modified asphalt when they were aged by means of the

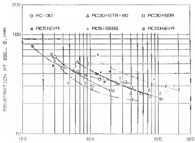


Figure 6.2 Pen-vis relationship for a selected modified asphalt blends at different TFOT and RTFOT aging conditions

TFOT and RTFOT processes. The aging trend of SBR and GTR-80 modified AC-30 tends to be shifted parallel from that for the original unmodified AC-30 asphalt.

6.4 Temperature Susceptibility as Measured by PVN'

Temperature susceptibility of a paving asphalt has been defined as the change in consistency of an asphalt for a given change in temperature. This parameter can be used to describe the change in rheological behavior of an asphalt over a wide range of temperature. A penetration-viscosity number (PVN') based on the penetration at 25 °C (77 °F) and the corresponding viscosity at 60 °C (140 °F) of paving asphalts was used to evaluate the temperature susceptibility of the modified asphalts. It is defined by the following equation [89]:

$$\mathrm{PVN'} = \frac{\{(6.4890 - 1.5900 \operatorname{Log} P) - (\operatorname{Log} V)\}}{(1.0500 - 0.2234 \operatorname{Log} P)} (-1.5) \qquad (6.2)$$

where

V = Absolute viscosity in poises at 60 °C (140 °F), and

P = Penetration at 25 °C (77 °F).

A high value of PVN' would indicate that a material has a low temperature susceptibility.

The results of absolute viscosity are shown in Appendix C-1. Table 6.1 shows the PVN's of the original and that of TFOT and RTFOT residues for the modified asphalt blends. As

Table 6.1 TFOT & RTFOT Effects on the pen-vis number from 25°C to 60°C (77°F to 140°F)

Asphalt	Original		Oven Temperature 141°C Pen-Vis Number (25 to 60°C)	 163°C	 185°C
AC-30	-0.44	TFOT	-0.98	-0.29	-0.22
		RTFOT	-0.21	-0.12	0.18
AC-30+ 5% Gilsonite	-0.03	TFOT	-0.34	-0.02	-0.01
		RTFOT	-0.28	-0.12	0.21
AC-30+ 10% Carbon Black	-0.33	TFOT	-0.21	-0.05	-0.12
		RTFOT	-0.23	-0.18	0.03
			163°C	185°C	198°C
AC-30+ 9% GTR-80	0.11	TFOT	0.30	0.63	1.34
		RTFOT	0.57	0.87	1.13
AC-30+ 15% GTR-40	1.02	TFOT	1.28	1.71	2.12
		RTFOT	-	-	-
AC-10+ 3.5% SBR	0.45	TFOT	0.22	0.93	1.54
		RTFOT	0.92	0.98	1.34
AC-30+ 5% EVA	-0.50	TFOT	-0.28	-0.61	-0.32
		RTFOT	-0.53	0.09	0.49
AC-30+ 8% SEBS	1.83	TFOT	1.37	1.11	1.48
		RTFOT	1.11	1.39	1.98
AC-20+ 9% EVA	-0.48	TFOT	-0.88	-0.35	-0.10
		RTFOT	-0.37	0.28	0.51
AC-5+ 5% EVA	-0.84	TFOT	-0.81	-0.30	0.28
		RTFOT	-0.43	0.84	0.84
AC-20+ 3.5% SEBS	2.22	TFOT	1.78	1.93	2.18
		RTFOT	1.08	1.12	1.43
AC-5+ 3.5% SEBS	1.04	TFOT	0.49	0.90	2.03
		RTFOT	1.93	2.28	2.30

seen from Table 6.1, the PVN' value generally increases after the TFOT and RTFOT aging. This means that the TFOT and RTFOT aging process tend to lower the temperature susceptibility of the modified asphalt blends.

Comparison of each main effect was done by means of Duncan's multiple-range test at a significant level of 0.05. The results of the Duncan's test, which are given in Table 6.2, indicate that SEBS lowers the temperature susceptibility of the base asphalt the most, while EVA reduces it the least as measured by pen-vis number.

The change in temperature susceptibility of the modified asphalt with aging can also be observed from the viscosity-temperature plots for the original and aged asphalt blends. It was observed that the shape of the viscosity-temperature relationship of the TFOT residue was slightly different from that for the original asphalt. As seen from Figure 6.3, the temperature susceptibility of the aged modified asphalt blends is slightly lower than that of the original unaged modified asphalt blends. This trend is different from that of the unmodified asphalt where the shape of viscosity-temperature plot is shifted parallel after the TFOT aging process [14]. This difference becomes more apparent as the oven temperature increased. This might be due to the imparted elastic properties of the modifiers in the asphalts.

Table 6.2 Duncan's grouping of polymer modified asphalts on the basis of pen-vis number

Asphalts

Duncan Grouping	Mean	N	ASPHALT
A	1.655	6	AC5+3.5% SEBS
A			
A	1.583	6	AC20+3.5% SEBS
A			
A	1.400	6	AC30+5% SEBS
B	0.988	6	AC30+3.5% SBR
B			
B	0.807	6	AC30+5% GTR-80
C	0.070	6	AC5+5% EVA
C			
C	-0.155	6	AC20+5% EVA
C			
C	-0.200	6	AC30+5% EVA

Oven_type

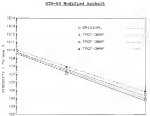
Duncan Grouping	Mean	N	OVEN
A	0.9112	24	RTFOT
B	0.6258	24	TFOT

Temperature

Duncan Grouping	Mean	N	TEMP(°C)
A	1.151	16	196
B	0.752	16	185
C	0.403	16	163

NOTE: Means with the same letter are not significantly different (Alpha =0.05)

GTR-80 Modified Asphalt



Regression Equation

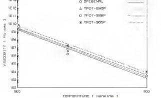
$\text{Log(vis)} = B_0 + B_1 \text{ Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
B_0	210.154	204.191	195.135	189.484
B_1	-74.311	-72.061	-68.678	-65.715
Standard Error of B_1	4.846	4.063	7.969	2.100
R-Square	0.956	0.997	0.987	0.999

Figure 6.3 TFOT effects on the viscosity temperature relationship of modified asphalts

Unmodified AC-30



Regression Equation

$\text{Log(vis)} = \beta_0 + \beta_1 \text{ Log(Temp)}$

Vis = in poises

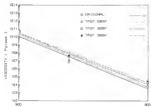
Temp = in Rankine

Regression Output

	Original	TFOT-285°F	TFOT-325°F	TFOT-365°F
β_0	216.956	215.181	210.611	209.020
β_1	-76.944	-76.236	-74.512	-73.823
Standard Error of β_1	15.455	10.985	9.731	5.194
R-Square	0.961	0.980	0.983	0.995

Figure 6.3 --Continued

Gilsonite Modified AC-30



Regression Equation

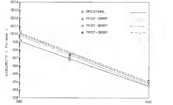
$\mathrm{Log(Vis)} = \beta_0 + \beta_1 \mathrm{Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-285°F	TFOT-325°F	TFOT-365°F
β_0	232.621	232.416	226.440	222.417
β_1	-82.462	-82.318	-80.046	-78.522
Standard Error of β_1	14.650	13.536	10.164	9.292
R-Square	0.969	0.974	0.984	0.986

Figure 6.3 --Continued

Carbon Black Modified AC-30



Regression Equation

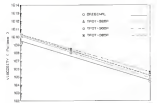
$\text{Log(vis)} = \beta_0 + \beta_1 \text{ Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-285°F	TFOT-325°F	TFOT-365°F
β_0	202.273	222.609	221.549	220.541
β_1	-71.569	-78.852	-78.369	-77.943
Standard Error of β_1	3.417	10.793	10.489	7.741
R-Square	0.998	0.981	0.982	0.990

Figure 6.3--Continued

GTR-40 Modified AC-30



Regression Equation

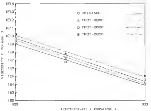
Log(vis)=B_0 + B_1 Log(Temp)
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
B_0	178.540	189.096	183.044	171.945
B_1	-62.620	-66.310	-64.014	-59.871
Standard Error of B_1	8.948	1.676	1.581	0.179
R-Square	0.980	0.959	0.999	0.999

Figure 6.3 --Continued

SBR Modified AC-30



Regression Equation

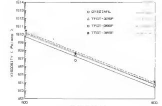
$\text{Log(vis)} = \beta_0 + \beta_1 \text{ Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-365°F
β_0	166.012	196.956	196.207	189.369
β_1	-65.562	-68.717	-66.340	-65.679
Standard Error of β_1	6.066	4.262	6.669	5.991
R-Square	0.992	0.996	0.964	0.992

Figure 6.3 --Continued

EVA Modified AC-30



Regression Equation

$$\text{Log(vis)} = \beta_0 + \beta_1 \,\text{Log(Temp)}$$

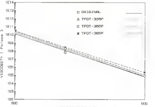
Vis = in poises
Temp = in Rankins

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
β_0	226.272	223.183	226.814	226.400
β_1	-80.221	-78.971	-80.262	-80.041
Standard Error of β_1	11.170	5.414	6.574	5.006
R-Square	0.981	0.995	0.993	0.996

Figure 6.3--Continued

SEBS Modified AC-30



Regression Equation

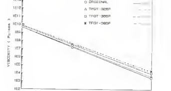
$\text{Log(vis)} = B_0 + B_1 \text{ Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
B_0	191.007	194.353	193.414	185.908
B_1	-67.015	-68.200	-67.804	-64.992
Standard Error of B_1	5.788	4.352	0.298	1.219
R-Square	0.992	0.996	0.999	0.999

Figure 6.3 --Continued

EVA Modified AC-20



Regression Equation

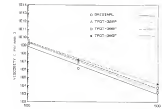
Log(vis)=B_0 + B_1 Log(Temp)
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
B_0	224.291	216.633	211.347	203.851
B_1	-79.514	-76.678	-74.653	-71.869
Standard Error of B_1	1.267	2.522	2.989	3.484
R-Square	0.999	0.999	0.998	0.998

Figure 6.3 --Continued

EVA Modified AC-5



Regression Equation

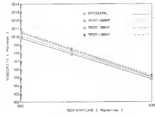
$\mathrm{Log(vis)} = \beta_0 + \beta_1 \mathrm{Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
β_0	212.029	213.224	206.869	192.203
β_1	-75.258	-75.538	-73.152	-67.702
Standard Error of β_1	10.389	4.057	5.539	4.289
R-Square	0.981	0.997	0.994	0.996

Figure 6.3 --Continued

SEBS Modified AC-20



Regression Equation

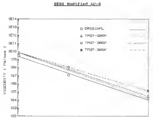
$\text{Log(vis)} = \beta_0 + \beta_1 \text{ Log(Temp)}$
Vis = in poises
Temp = in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
β_0	182.057	184.128	195.157	194.274
β_1	-63.805	-64.477	-68.422	-68.047
Standard Error of β_1	1.274	3.198	1.111	0.146
R-Square	0.999	0.998	0.999	0.999

Figure 6-3 --Continued

SEBS Modified AC-5



Regression Equation

$\text{Log(vis)} = \beta_0 + \beta_1 \text{ Log(Temp)}$
Vis = in poises
Temp - in Rankine

Regression Output

	Original	TFOT-325°F	TFOT-365°F	TFOT-385°F
β_0	193.378	204.061	195.048	173.483
β_1	-68.165	-71.949	-68.595	-60.609
Standard Error of β_1	5.468	2.381	3.287	0.023
R-Square	0.994	0.999	0.998	0.999

Figure 6.3 --Continued

6.5 Aging Characteristics as Measured by Penetration Retained

The results of the penetration tests at temperatures of 4 and 25 °C (39.2 and 77 °F) are given in Appendixes C-2 and C-3, respectively. Appendixes C-4 and C-5 show the percent penetration retained at two temperatures. It was observed that the coarse ground tire rubber modified asphalt binders spilled out from the bottles during the RTFOT process. It was therefore concluded that the RTFOT process was not suitable for the coarse ground tire rubber modified asphalts.

Results of ANOVA on the percent penetration retained at temperatures of 4 and 25 °C (39.2 and 77 °F) are given in Tables 6.3 and 6.4, respectively. Table 6.3 shows that all three main effects and the interaction effects are significant, with the exception of the interaction of oven type and temperature. The insignificance of the interaction between oven type and temperature means that the difference between the TFOT and RTFOT is not dependent on the oven temperature. From Appendixes C-3 and C-5, it can be seen that the AC-20 blended with EVA has the lowest percent penetration retained value, and the AC-30 blended with fine ground tire rubber has the highest value. This indicates that the ground tire rubber modifier provides the best anti-aging characteristics when compared with the other modifiers. It is also seen that the RTFOT is a more severe aging process than the TFOT for the asphalt blends studied.

Table 6.3 Results of ANOVA on Penetration Retained at 4°C (39.2°F)

Model: $Y_{ijk} = m + A_i + O_j + T_k + A*O_{ij} + A*T_{ik} + O*T_{jk} + \epsilon_{ijk}$

Asphalt Modified with Carbon Black & Gilsonite

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	2	72.574444	36.287222	6.73	0.0525
OVEN	1	1.445000	1.445000	0.27	0.6320
TEMP	2	1273.754444	636.877222	118.14	0.0003
ASPHALT*OVEN	2	377.363333	188.681667	35.00	0.0029
ASPHALT*TEMP	4	65.585556	16.396389	3.04	0.1534
OVEN*TEMP	2	57.663333	28.831667	5.35	0.0741

R-Square = 0.988

Asphalts Modified with Polymers

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	7	1808.948125	258.421161	18.25	0.0001
OVEN	1	669.760208	669.760208	47.29	0.0001
TEMP	2	2981.961667	1490.980833	105.28	0.0001
ASPHALT*OVEN	7	1149.514792	164.216399	11.60	0.0001
ASPHALT*TEMP	14	595.725000	42.551786	3.00	0.0241
OVEN*TEMP	2	8.251667	4.125833	0.29	0.7517

R-Square = 0.973

Table 6.4 Results of ANOVA on Penetration Retained at 25°C (77°F)

Model: $Y_{ijk} = m + A_i + O_j + T_k + A*O_{ij} + A*T_{ik} + O*T_{jk} + \epsilon_{ijk}$

Asphalt Modified with Carbon Black & Gilsonite

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	2	686.634444	343.317222	111.50	0.0003
OVEN	1	252.375556	252.375556	82.26	0.0008
TEMP	2	1869.907778	934.953889	304.74	0.0001
ASPHALT*OVEN	2	21.614444	10.807222	3.52	0.1312
ASPHALT*TEMP	4	56.572222	14.143056	4.61	0.0840
OVEN*TEMP	2	21.807778	10.903889	3.55	0.1297

R-Square = 0.956

Asphalt Modified with Polymers

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	7	840.941725	120.134532	14.35	0.0001
OVEN	1	1123.461008	1123.461008	134.24	0.0001
TEMP	2	2434.061267	1217.030633	145.42	0.0001
ASPHALT*OVEN	7	908.595725	129.799389	15.51	0.0001
ASPHALT*TEMP	14	185.116200	13.222586	1.58	0.2013
OVEN*TEMP	2	37.832267	18.916133	2.26	0.1410

R-Square = 0.979

6.6 Aging Characteristics as Observed from Low-Temperature Viscosity

The most important purpose of Schweyer rheometer test is to characterize the rheological behavior of asphalts at low service temperatures.

Appendixes C-6 and C-7 display the results of Schweyer rheometer tests at temperatures of 5 °C (41 °F) and 25 °C (77 °F), respectively.

Since the original viscosities are quite different from each other, it is more appropriate to use the viscosity ratios in the analysis. Results of ANOVA on the constant power viscosity ratios at 5 and 25 °C (41 and 77 °F) are summarized in Tables 6.5 and 6.6, respectively. From Table 6.5, it is seen that the main effect of oven type and the interaction between asphalt blends and oven temperatures are not significant. This indicates that the TFOT and RTFOT are not significant different from one another on the basis of constant power viscosity ratio for the modified asphalts at the temperature of 5 °C (41 °F). However, on the basis of viscosity at 25 °C (77 °F) (Table 6.6), all three main effects and the interaction effects except for the interaction between asphalt and oven temperature are significant.

The comparison of the two types of oven was done at three different temperatures by means of Duncan's multiple-range test at a significance level of 0.05. Table 6.7 shows the results of the Duncan's test. The test results show that the RTFOT produces a more severe aging effect than the TFOT at all three oven temperatures.

Table 6.5 Results of ANOVA on the basis of Constant Power Viscosity ratio at 5°C (41°F)

$$Y_{ijk} = m + A_i + O_j + T_k + A*O_{ij} + A*T_{ik} + O*T_{jk} + \epsilon_{ijk}$$

Asphalt Modified with Carbon Black & Gilsonite

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT[1]	2	355.51803	177.75902	23.13	0.0063
OVEN	1	2.77694	2.77694	0.36	0.5802
TEMP	2	69.04510	34.52255	4.49	0.0949
ASPHALT*OVEN	2	4.92921	2.46461	0.32	0.7427
ASPHALT*TEMP	4	95.57607	23.89402	3.11	0.1489
OVEN*TEMP	2	17.95614	8.97807	1.17	0.3985

R-Square = 0.9467

Asphalt Modified with Polymers

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT[2]	7	84.842765	12.120395	135.03	0.0001
OVEN	1	0.299252	0.299252	3.33	0.0893
TEMP	2	49.245329	24.622665	274.31	0.0001
ASPHALT*OVEN	7	9.042131	1.291733	14.39	0.0001
ASPHALT*TEMP	14	64.649604	4.617829	51.45	0.0001
OVEN*TEMP	2	0.668404	0.334202	3.72	0.0505

R-Square = 0.9940

Table 6.6 Results of ANOVA on the basis of Constant Power Viscosity ratio at 25°C (77°F)

$$Y_{ijk} = m + A_i + O_j + T_k + A{*}O_{ij} + A{*}T_{ik} + O{*}T_{jk} + \epsilon_{ijk}$$

Asphalts Modified with Carbon Black & Gilsonite

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT[1]	2	31.17924	15.58962	45.72	0.0018
OVEN	1	22.87134	22.87134	67.07	0.0012
TEMP	2	137.81554	68.90777	202.08	0.0001
ASPHALT*OVEN	2	3.52804	1.76402	5.17	0.0777
ASPHALT*TEMP	4	14.82142	3.70536	10.87	0.0201
OVEN*TEMP	2	3.88321	1.94161	5.69	0.0676

R-Square = 0.9937

Asphalts Modified with Polymers

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT[2]	7	371.58906	53.08415	19.84	0.0001
OVEN	1	136.58627	136.58627	51.05	0.0001
TEMP	2	318.92753	159.46376	59.60	0.0001
ASPHALT*OVEN	7	91.23591	13.03370	4.87	0.0058
ASPHALT*TEMP	14	90.52590	6.46614	2.42	0.0552
OVEN*TEMP	2	29.32426	14.66213	5.48	0.0175

R-Square = 0.965

Table 6.7 Duncan's grouping of oven type by temperature on the basis of constant power viscosity ratio at 25°C (77°F)

Temp.	Duncan Grouping	Mean	N	OVEN
163°C	A	4.287	8	RTFOT
	B	2.963	8	TFOT
185°C	A	7.713	8	RTFOT
	B	4.034	8	TFOT
196°C	A	12.418	8	RTFOT
	B	7.300	8	TFOT

NOTE: Means with the same letter are not significantly different from one another (Alpha= 0.05)

The results of comparison of the three oven temperatures done at two different oven types by means of Duncan's multiple-range test at a significance level of 0.05 are given in Table 6.8. The analysis results indicate that the process temperature of 196 °C (385 °F) gives a significantly more severe effect than the other two process temperatures for both oven types. However, the process temperatures of 185 and 163 °C (365 & 325 °F) are not significantly different from one another.

6.7 Aging Characteristics as Observed from Results of Infrared Spectroscopy

The most important purpose of infrared spectroscopy is to identify the changes in functional groups of asphalt after aging. Study of the infrared spectrum indicates that the infrared absorption spectrum between 1600 cm^{-1} and 1900 cm^{-1} is of particular interest since it contains the absorption bands for the functional groups of carboxylic acids, ketones, and anhydrides [74,75]. Ketones and anhydrides are formed in asphalt on oxidative aging, while carboxylic acids occur naturally in asphalt but increase in amount on oxidative aging. Also, the absorbance band centering at about 1600 cm^{-1} can be assumed to be fairly constant, since it results primarily from aromatic carbon-carbon double bonds which are present in highly condensed stable molecules [49]. Therefore, the carbonyl ratio, which is the ratio of absorbance at 1700 cm^{-1} and 1600 cm^{-1}, was used to indicate the level of oxidation

Table 6.8 Duncan's grouping of temperature by oven type on the basis of constant power viscosity ratio at 25°C (77°F)

Oven type	Duncan Grouping	Mean	N	TEMP(°C)
TFOT	A	7.300	8	196
	B	4.034	8	185
	B	2.963	8	163
RTFOT	A	12.418	8	196
	B	7.713	8	185
	C	4.287	8	163

NOTE: Means with the same letter are not significantly different from one another (Alpha=0.05) of the binders. The change in oxidation level due to TFOT and RTFOT aging was expressed by means of carbonyl ratio indexes, which is the ratio of the aged carbonyl ratio to the original unaged carbonyl ratio.

The results of the infrared spectroscopy tests are given in Appendixes C-8 and C-9. Results of ANOVA on the carbonyl ratio indices, which are summarized in Table 6.9, indicate that all three main effects and interaction effects are significant.

Comparison of the effects of oven type was done at different temperatures by means of Duncan's multiple-range test at a significance level of 0.05. The results, which are summarized in Table 6.10, indicate that the effects of TFOT and RTFOT are significantly different at any of three oven temperatures. Also, the results from the comparison of temperatures at oven type by means of Duncan's test, which are given in Table 6.11, indicate that the effects of temperatures are significantly different from each other for both oven types.

6.8 Summary of Findings

The major findings for this study on modified asphalt binders are as follows:

1. It appears that the RTFOT aging process performed at a temperature of 185 °C (365 °F) can simulate a one-year field aging effect under typical Florida conditions.

Table 6.9 Results of ANOVA on the basis of Carbonyl Ratio Indices

$$Y_{ijk} = m + A_i + O_j + T_k + A*O_{ij} + A*T_{ik} + O*T_{jk} + \varepsilon_{ijk}$$

Asphalts Modified with Polymers

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	7	0.78854026	0.11264861	61.45	0.0001
OVEN	1	0.29902046	0.29902046	163.11	0.0001
TEMP	2	0.47137323	0.23568662	128.56	0.0001
ASPHALT*OVEN	7	0.07755396	0.01107914	6.04	0.0022
ASPHALT*TEMP	14	0.11628066	0.00830576	4.53	0.0039
OVEN*TEMP	2	0.01383834	0.00691917	3.77	0.0489

R-Square = 0.9857

Table 6.10 Duncan's grouping of oven type by temperature on the basis of carbonyl ratio index

Temp.	Duncan Grouping	Mean	N	OVEN
163°C	A	1.3074	8	RTFOT
	B	1.1101	8	TFOT
185°C	A	1.4193	8	RTFOT
	B	1.2576	8	TFOT
196°C	A	1.5085	8	RTFOT
	B	1.3940	8	TFOT

NOTE: Means with the same letter are not significantly different (Alpha= 0.05)

Table 6.11 Duncan's grouping of temperature by oven type on the basis of carbonyl ratio index

Oven type	Duncan's Grouping	Mean	N	TEMP(°C)
TFOT	A	1.3940	8	196
	B	1.2576	8	185
	C	1.1101	8	163
RTFOT	A	1.5085	8	196
	B	1.4193	8	185
	C	1.3074	8	163

NOTE: Means with the same letter are not significantly different (Alpha= 0.05)

2. The temperature susceptibility of modified asphalt blends decreases slightly after the TFOT or RTFOT aging process as determined by the viscosity-temperature plots and the pen-vis numbers (PVN') that are based on penetration at 25 °C (77 °F) and absolute viscosity at 60 °C (140 °F).
3. Modified AC-30 asphalts appear to have lower aging rate than those of the modified AC-5 asphalts. However, modification of AC-5 gives the most benefits in terms of lowering the temperature susceptibility of the asphalt binder.
4. The RTFOT is a more severe aging process than the TFOT at any of the three process temperatures as seen from the percent penetration retained and absolute viscosity ratio of the aged modified asphalts.
5. The TFOT and RTFOT are not significantly different from one another as seen from the low-temperature constant power viscosity ratio of the aged modified asphalts.
6. The RTFOT was not suitable for use on the coarse ground tire rubber modified asphalts because the modified asphalt binders spilled out from the bottles during the RTFOT process.
7. Modifier SEBS lowers the temperature susceptibility of the asphalts the most, while EVA reduces the temperature susceptibility the least as seen from the pen-vis numbers.

8. On the basis of carbonyl ratio, the effects of TFOT and RTFOT are significantly different at all three oven temperatures.
9. The modified asphalts which are superior to AC-30 on the basis of aging characteristics include (1) AC-20 + 3.5% SEBS, (2) AC-30 + 5% SEBS, and (3) AC-30 + 5% GTR-80.

CHAPTER 7
RESULTS OF MIXTURE STRENGTH TESTS

7.1 Introduction

An experimental program was conducted to evaluate different modifiers on the effects of indirect tensile strength, resilient modulus and fracture energy using Marshall dense-graded and open-graded specimens. In addition, evaluation of aging characteristics of modified asphalt mixtures by means of strength ratio and modulus ratio will be performed in this section. The detailed program has been presented in Chapter 3

7.2 Analysis Method

Statistical analysis using the ANOVA technique was used to determine whether the effect of main factors and interactions of factors are significant.

The effects of asphalt blend type and exposure duration were evaluated at each fixed forced-draft oven or natural sunlight exposure condition. The statistical model for this design is as follows:

$$Y_{ijk} = \mu + A_i + E_j + (AE)_{ij} + \epsilon_{ijk}$$

where

$i = 1,2,\ldots,11$

j = 1,2,3

k = 1,2

Y_{ijk} = the response of the kth replicate on the ith asphalt and jth exposure duration

μ = overall mean

A_i = main effect of the ith asphalt blend

D_j = main effect of the jth exposure duration

$(AD)_{ij}$ = the effect of the interaction of the ith asphalt and jth exposure duration

ϵ_{ijk} = experimental error

7.3 Effects of Modifiers on the Resilient Modulus

The resilient modulus of an asphalt concrete can directly be related to the structural contribution of that layer or that component of the pavement. The resilient modulus is defined as the ratio of applied stress to corresponding recoverable strain during repeated loading. Mixtures with high resilient modulus at the low temperature are considered to be too brittle to resist cracking caused by thermal and load effects. It also has been found that the resilient modulus versus temperature relationship could be employed to aid the quality control of the asphalt concrete mixtures over the temperature range where the pavement will face in the field. This section presents the evaluation of the influence of modifiers on the resilient modulus of different types of mixtures. The effects of testing cycle frequency and rotation will also be assessed

7.3.1 Effects of Cycle Frequency and Rotation

Results of the resilient modulus tests on both dense-graded and open-graded mixtures at temperatures of 5°C (41°F) and 25°C (77°F) are tabulated in Appendixes D-1 and D-2, respectively. Statistical analysis using the ANOVA technique was employed to determine the significance of the effects of test cycle frequency and test specimen rotation on the measured total resilient modulus. Duncan's multiple comparison test were performed on the significant main factors. The results are also shown in Appendixes D-1 and D-2 along with the resilient modulus values for each mixture.

The results indicate that the rotation of specimen during the test appears to have a significant effect on the measured total resilient modulus at 5°C (41°F) of the unmodified and modified dense-graded asphalt mixtures. The measured resilient modulus after 90° rotation is generally less than that measured at the initial position. At temperature of 25°C (77°F), the resilient modulus of the SBR, EVA, and SEBS modified asphalt mixtures after 90° rotation is generally greater than that measured at the initial position. This might be explained by the possibility that the specimen were further compacted when loaded at the initial test position, resulting in an increase in resilient modulus.

The effect of the test cycle frequency on the measured total resilient modulus at temperature of 5°C (41°F) is not significant for either the unmodified or the modified asphalt mixtures. It appears that the elastic property of the material become more apparent at this low temperature. However, at temperature of 25°C (77°F), the resilient modulus appears to increase slightly as the cycle frequency increases. This observation is more noticeable among the polymer modified asphalt mixtures, such as CTR-80 and SEBS modified asphalt mixtures. This can be explained by the fact that a higher test cycle frequency would result in a shorter resting time for the loaded specimen to rebound elastically between the pulsed loads. If a tested specimen does not rebound completely, the total recovered strain would be lower and the determined resilient modulus would be higher. Modified asphalts with more pronounced delayed elastic behavior would be affected more by the shortening of the resting time.

7.3.2 Effects of Modifiers on Dense-Graded Mixtures

The results of ANOVA on the measured total and instantaneous resilient modulus for dense-graded mixture are shown in Table 7.1. The test results indicated that the forced-draft oven produces the most severe rate of age-hardening on the measured total and instantaneous resilient modulus at temperatures of 5°C (41°F) and 25°C (77°F). As seen from the mean values from Duncan's multiple comparison test, the forced-draft oven increases the resilient modulus approximately two fold at a temperature of 25°C (77°F). However, the natural 6-month roof aging process is not significantly different from the no-aging condition on the

Table 7.1 Results of ANOVA and Duncan's grouping on the effects of exposure conditions for dense-graded mixtures

$$\text{Model}= \mu + A_i + E_j + (AE)_{ij} + \epsilon_{ijk}$$

On Basis of Total Resilient Modulus

TEMPERATURE=41°F

Source	DF	Anove SS	F Value	Pr > F
ASPHALT	10	2.08410E+12	24.38	0.0001
DURATION	2	1.49293E+12	87.31	0.0001
ASPHALT*DURATION	20	4.93167E+11	2.88	0.0034

R-Square= 0.9392

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1764150	22	Force-Draft Oven (90 days)
B	1484498	22	Roof Aging(8 months)
C	1416630	22	Original(No Aging)

TEMPERATURE= 77°F

Source	DF	Anove SS	F Value	Pr > F
ASPHALT	10	1.61580E+12	67.18	0.0001
DURATION	2	2.95481E+12	614.25	0.0001
ASPHALT*DURATION	20	1.77157E+11	3.68	0.0005

R-Square= 0.984

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1125435	22	Force-Draft Oven (98 days)
B	678647	22	Roof Aging(8 months)
B			
B	874995	22	Original(No Aging)

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 7-1 -- Continued

$$\text{Model} = \mu + A_i + E_j + (AE)_{ij} + \epsilon_{ijk}$$

On Basis of Instantaneous Resilient Modulus

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	2.49176E+12	24.66	0.0001
DURATION	2	1.06778E+12	53.28	0.0001
ASPHALT*DURATION	20	4.27137E+11	2.13	0.0263

R-Square= 0.924

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	2082154	22	Force-Draft Oven (90 days)
B	1644647	22	Roof Aging (6 months)
B			
B	1788887	22	No Aging

TEMPERATURE=77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	2.17580E+12	54.03	0.0001
DURATION	2	2.51568E+12	312.35	0.0001
ASPHALT*DURATION	20	2.39596E+11	2.97	0.0027

R-Square= 0.974

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1565806	22	Force-Draft Oven (90 days)
B	1166679	22	Roof Aging (6 months)
B			
B	1137942	22	No Aging

Note: Means with the same letter are not significantly different (Alpha= 0.05)

basis of measured total and instantaneous resilient modulus at temperature of 25°C (77°F). At the temperature of 5°C (41°F), the results show that the natural 6-month roof aging produces slightly higher aging affect than that of the unaged asphalt mixtures on the basis of measured total resilient modulus. Grouping of asphalt mixtures by exposure condition on the basis of total resilient modulus at temperatures of 5°C (41°F) and 25°C (77°F) are shown in Table 7.2. As seen from these tables, the SEBS modifier increases the resilient modulus at both 5°C (41°F) and 25°C (77°F) the most, whereas the SBR increases it the least at 25°C (77°F). The different grouping after aging indicated that different modified asphalt mixtures have different rate of age-hardening. Some of the modified asphalt mixtures aged faster than others.

7.3.3 Effects of Modifiers on Open-Graded Mixture

Results of ANOVA on the measured total and instantaneous resilient modulus for open-graded mixture are shown in Table 7.3. The test results indicated that the forced-draft oven type produces the most severe rate of age-hardening on the measured total and instantaneous resilient modulus at both 5°C (41°F) and 25°C (77°F). However, the effect of the natural 6-month roof aging process is not significantly different from that of the original no-aging process on the basis of measured total and instantaneous resilient modulus at 5°C (41°F) and 25°C (77°F). Grouping of asphalt mixtures by exposure condition on the basis of total resilient modulus at 5°C

Table 7.2 Grouping of dense-graded asphalt mixtures by exposure condition on the basis of total resilient modulus
5°C (41°F)

```
No Aging
Duncan Grouping              Mean      N  ASPHALT

              A           1879530      2  AC30+SEBS
              A
     B        A           1812280      2  AC30+EVA
     B
     B        C           1673480      2  AC30+Gilsonite
              C
     D        C           1607035      2  AC20+SEBS
     D        C
     D        C           1587815      2  AC30+Carbon Black
     D
     D        E           1473475      2  AC20+EVA
              E
     F        E           1353225      2  AC30+GTR-80
     F        E
     F        E           1352835      2  AC-30
     F
     F                    1297840      2  AC5+EVA
     F
     F                    1239845      2  AC30+SBR

              G           1072580      2  AC5+SEBS

Force-Draft oven
Duncan Grouping              Mean      N  ASPHALT

              A           2052085      2  AC30+EVA
              A
     B        A           1905550      2  AC20+SEBS
     B        A
     B        A           1904830      2  AC30+SEBS
     B        A
     B        A    C      1838510      2  AC30+Gilsonite
     B        A    C
     B        A    C      1808280      2  AC20+EVA
     B             C
     B        D    C      1748000      2  AC30+SBR
     B        D    C
     B        D    C      1723450      2  AC5+EVA
     B        D    C
     B        D    C      1687245      2  AC-30
              D    C
              D    C      1648780      2  AC30+Carbon Black
              D    C
              D    C      1581880      2  AC30+GTR-80
              D
              D           1521935      2  AC5+SEBS
```

Table 7.2 -- Continued

25°C (77°F)

No Aging

Duncan Grouping		Mean	N	ASPHALT
	A	982395	2	AC-30+SEBS
	B	803895	2	AC-30+EVA
	B			
C	B	779495	2	AC-20+SEBS
C	B			
C	B	776725	2	AC-20+EVA
C	B			
C	B	729185	2	AC-30+Carbon Black
C				
C	D	697245	2	AC-30+Gilsonite
	D			
E	D	622775	2	AC-30+SBR
E				
E	F	601150	2	AC-5+EVA
	F			
G	F	522935	2	AC-30
G				
G		480525	2	AC-30+GTR-80
G				
G		443585	2	AC-5+SEBS

Force-Draft oven

Duncan Grouping		Mean	N	ASPHALT
	A	1402380	2	AC-30+EVA
	A			
B	A	1311145	2	AC-20+EVA
B	A			
B	A	1297455	2	AC-20+SEBS
B	A			
B	A	1259310	2	AC-30+SEBS
B				
B	C	1212305	2	AC-30+Gilsonite
	C			
D	C	1075225	2	AC-30+SBR
D				
D		1042305	2	AC-5+EVA
D				
D		1023640	2	AC-30+Carbon Black
D				
D		1000100	2	AC-30
D				
D	E	942645	2	AC-5+SEBS
	E			
	E	813355	2	AC-30+GTR-80

Table 7.3 Results of ANOVA and Duncan's grouping on the effects of exposure conditions on basis of resilient modulus for open-graded mixture

$$\text{Model}= \mu + A_i + B_j + (AB)_{ij} + \epsilon_{ijk}$$

Total Resilient Modulus

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	3.14512E+11	6.85	0.0001
DURATION	2	1.85018E+11	19.58	0.0001
ASPHALT*DURATION	20	9.51860E+10	1.01	0.4805

R-Square= 0.7828

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1104858	22	Force-Draft Oven (90 days)
B	998805	22	Roof Aging(6 months)
B	989883	22	Original(No Aging)

TEMPERATURE= 77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	1.68306E+11	19.83	0.0001
DURATION	2	4.11553E+11	245.42	0.0001
ASPHALT*DURATION	20	3.98243E+10	2.37	0.0134

R-Square= 0.8573

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	853988	22	Force-Draft Oven (90 days)
B	493863	22	Roof Aging(6 months)
B			
B	479721	22	Original(No Aging)

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 7.3 -- Continued

Model= $\mu + A_i + B_j + (AB)_{ij} + \epsilon_{ijk}$

Instantaneous Resilient Modulus

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	2.42848E+11	4.28	0.0007
DURATION	2	2.06703E+11	9.99	0.0004
ASPHALT*DURATION	20	1.55712E+11	0.75	0.7456

R-Square= 0.702

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1449938	22	Force-Draft Oven (90 days)
B	1334897	22	Roof Aging (6 months)
B			
B	1327861	22	No Aging

TEMPERATURE=77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	4.14001E+11	7.96	0.0001
DURATION	2	8.40696E+11	80.84	0.0001
ASPHALT*DURATION	20	8.95100E+10	0.86	0.6313

R-Square= 0.889

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1124705	22	Force-Draft Oven (90 days)
B	895731	22	Roof Aging (6 months)
B			
B	876061	22	No Aging

Note: Means with the same letter are not significantly different (Alpha= 0.05)

(41°F) and 25°C (77°F) are shown in Table 7.4. As seen from these tables, the SEBS modifier increases the resilient modulus at 25°C (77°F) the most, whereas the EVA modifier increases it the least. However, the gilsonite modifier increases the resilient modulus at 5°C (41°F) the most as compared with the other modifiers.

7.3.4 Comparison Between Dense-Graded and Open-Graded Mixtures

All of the modified open-graded asphalt mixtures show lower value of resilient modulus than that of dense-graded asphalt mixtures at both 5°C (41°F) and 25°C (77°F) as seen from these statistical analysis. This behavior is reasonable and as anticipated. The higher air void content in the open-graded mix would cause a higher recovered strain, and therefore the determined resilient modulus would be lower.

The rate of age-hardening of asphalt mixtures caused by the forced-draft oven process are characterized by means of the ratio of resilient modulus after and before the aging process. Table 7.5 shows the ratio of resilient modulus for the dense- and open-graded mixtures at temperatures of 5°C (41°F) and 25°C (77°F). All of the modulus ratios are plotted in bar charts. Figures 7.1 and 7.2 illustrate the comparison between the dense-graded and open-graded mixtures on the basis of resilient modulus ratio at temperatures of 5°C (41°F) and 25°C (77°F), respectively. As seen from these figures, the rate of age-hardening of open-graded mixtures is lower than that of dense-graded mixtures. It appears that the aggregate

Table 7.4 Grouping of open-graded asphalt mixtures by exposure condition on basis of total resilient modulus

5°C (41°F)

No Aging

Duncan Grouping		Mean	N	ASPHALT
	A	1111986	2	AC30+Gilsonite
	A			
	A	1111888	2	AC30+EVA
	A			
	A	1101475	2	AC30+GTR-80
	A			
	A	1084686	2	AC20+SEBS
	A			
B	A	1036751	2	AC30+SEBS
B				
B	C	928155	2	AC30+SBR
B	C			
B	C	923348	2	AC-30
B	C			
B	C	914852	2	AC30+Carbon Black
	C			
	C	894458	2	AC20+EVA
	C			
D	C	883731	2	AC5+SEBS
D				
D		765842	2	AC5+EVA

Force-Draft oven

Duncan Grouping		Mean	N	ASPHALT
	A	1176517	2	AC-30
	A			
	A	1161899	2	AC30+Gilsonite
	A			
	A	1157283	2	AC30+EVA
	A			
	A	1153115	2	AC30+GTR-80
	A			
	A	1144182	2	AC20+SEBS
	A			
	A	1141772	2	AC30+SEBS
	A			
B	A	1098704	2	AC30+Carbon Black
B	A			
B	A	1088746	2	AC20+EVA
B	A			
B	A	1075195	2	AC30+SBR
B	A			
B	A	1070144	2	AC5+SEBS
B				
B		1013866	2	AC5+EVA

Table 7.4 -- Continued

25°C (77°F)

No Aging

Duncan Grouping				Mean	B	ASPHALT
		A		586777	2	AC-30+SEBS
		A				
B		A		563003	2	AC-30+Gilsonite
B		A				
B		A	C	556978	2	AC-30+EVA
B		A	C			
B	D	A	C	547673	2	AC-20+SEBS
B	D		C			
B	D	E	C	498567	2	AC-30+GTR-80
	D	E	C			
	D	E	C	476042	2	AC-30+Carbon Black
	D	E				
	D	E		462871	2	AC-30+SBR
		E				
F		E		437704	2	AC-20+EVA
F		E				
F		E		433779	2	AC-30
F						
F		G		372962	2	AC-5+SEBS
		G				
		G		339827	2	AC-5+EVA

Force-Draft oven

Duncan Grouping			Mean	N	ASPHALT
	A		715520	2	AC-30+Gilsonite
	A				
B	A		699374	2	AC-20+SEBS
B	A				
B	A		688634	2	AC-30+EVA
B	A				
B	A	C	674893	2	AC-30+GTR-80
B	A	C			
B	A	C	672079	2	AC-30+SEBS
B		C			
B	D	C	652555	2	AC-20+EVA
B	D	C			
B	D	C	650645	2	AC-5+SEBS
	D	C			
E	D	C	625513	2	AC-30
E	D	C			
E	D	C	624450	2	AC-30+SBR
E	D				
E	D		608649	2	AC-30+Carbon Black
E					
E			580685	2	AC-5+EVA

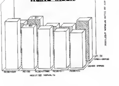
Table 7.5 Resilient modulus ratio after the forced-draft oven process of modified and unmodified asphalt concrete mixtures

5°C (41°F)

Asphalt Blend	Dense-graded Mixture	Open-graded Mixture
AC-5+SEBS	1.42	1.22
AC-30+SBR	1.41	1.16
AC-5+EVA	1.33	1.33
AC-30	1.23	1.27
AC-20+EVA	1.23	1.22
AC-20+SEBS	1.19	1.10
AC-30+GTR-80	1.10	1.05
AC-30+EVA	1.13	1.04
AC-30+Gilsonite	1.10	1.04
AC-30+SEBS	1.10	1.05
AC-30+Carbon Black	1.05	1.20

25°C (77°F)

Asphalt Blend	Dense-graded mixture	Open-graded mixture
AC-5+SEBS	2.13	1.74
AC-30	1.91	1.44
AC-30+GTR-80	1.77	1.35
AC-30+EVA	1.75	1.23
AC-30+Gilsonite	1.74	1.27
AC-5+EVA	1.74	1.71
AC-30+SBR	1.73	1.35
AC-20+EVA	1.69	1.49
AC-20+SEBS	1.66	1.20
AC-30+Carbon Black	1.40	1.28
AC-30+SEBS	1.20	1.15



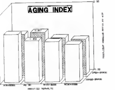


Figure 7.1 Comparison between dense-graded and open-graded mixtures on the basis of modulus ratio at 5°C(41°F)

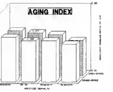
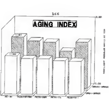


Figure 7.1 --Continued



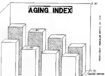


Figure 7.2 Comparison between dense-graded and open-graded mixture on the basis of modulus ratio at 25°C (77°F)

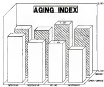


Figure 7.2 --Continued

plays an important role on the pavement age-hardening. In addition, all of the modified open-graded asphalt mixtures show slower rate of age-hardening than that of conventional unmodified AC-30 asphalt mixture as seen from the ratio of resilient modulus at 5°C (41°F). On the basis of the ratio of resilient modulus at 25°C (77°F), all of the modified open-graded asphalt mixtures, with the exception of those containing EVA and SEBS modified AC-5, also show slower rate of age-hardening than that of the unmodified AC-30 asphalt mixture. It appears that the combination of proper modified asphalt binders and proper aggregate type and gradation could slow down the age-hardening of the asphalt pavement.

7.4 Effects of modifiers on the tensile strength

The indirect tensile strength is the maximum tensile stress that the specimen can withstand. This test has been used for characterizing the resistance to failure of asphalt concrete caused by tensile stresses. It is usually used to simulate the stress state caused by wheel loads in the lower position of asphalt concrete layer and the stress state at the pavement surface due to the temperature dropping. Another important property obtained from the indirect tensile test is the stress-strain characteristics. The tensile failure strain is usually used for predicting cracking potential. Mixes that can tolerate high strains prior to failure are more likely to resist cracking than the mix that cannot endure high strains.

Tabulated results in Appendices D-3 and D-4 were used to evaluate the effects of modifiers on the measured indirect tensile strength for both dense-graded and open-graded mixtures at low temperatures and the comparison between dense-graded and open-graded mixtures on the basis of indirect tensile strength and strength ratio.

7.4.1 Effects of Modifiers on Dense-Graded Mixtures

Results of ANOVA on the indirect tensile strength for dense-graded mixtures are shown in Table 7.6. The test results indicated that the forced-draft oven type produces the most severe rate of age-hardening as measured by the indirect tensile strength at temperature 25°C (77°F). The specimens that were aged in the forced-draft oven had approximately a tensile strength of 290 psi, whereas the original unaged mixtures had only 190 psi at temperature of 25°C (77°F). Unfortunately, at the temperature of 5°C (41°F), the results show some variations on the measured tensile strength for aged and unaged modified asphalt mixtures. Grouping of asphalt mixtures by exposure condition on the basis of indirect tensile strength at temperature of 25°C (77°F) for dense-graded mixtures are shown in Table 7.7. As seen from this table, the SEBS modifier increases the strength the most at temperature of 25°C (77°F). However, it can be seen that the modifiers EVA and SEBS modified with AC-5 did not provide the same indirect tensile strength as the mixtures containing conventional AC-30 asphalt at temperature of 25°C (77°F).

Table 7.6 Results of ANOVA and Duncan's grouping on the effects of exposure conditions on basis of indirect tensile strength

Model: $\mu + A_i + E_j + (AE)_{ij} + \epsilon_{ijk}$

Dense-graded mixtures

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	66505.43496	11.29	0.0001
DURATION	2	6422.72624	5.45	0.0090
ASPHALT*DURATION	20	17714.76489	1.50	0.1457

R-Square= 0.823

Duncan Grouping		Mean	N	EXPOSURE CONDITION
	A	465.560	22	Original(No Aging)
B	A	451.689	22	Force-Draft Oven (90 days)
B		441.490	22	Roof Aging(6 months)

TEMPERATURE= 77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	123105.0581	120.09	0.0001
DURATION	2	118941.2853	580.14	0.0001
ASPHALT*DURATION	20	8653.1461	4.22	0.0001

R-Square= 0.987

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	286.946	22	Force-Draft Oven (90 days)
B	198.705	22	Roof Aging(6 months)
B	194.322	22	Original(No Aging)

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 7.7 Grouping of dense-graded asphalt mixtures by exposure condition on the basis of indirect tensile strength at temperature of 77°F

```
No Aging
Duncan Grouping              Mean      N  ASPHALT

              A           258.800      2  AC-30+SEBS

              B           247.545      2  AC-30+EVA
              B
              B           238.900      2  AC-30+Gilsonite

              C           213.700      2  AC-20+SEBS

              D           201.050      2  AC-20+EVA
              D
              D           197.095      2  AC-30+Carbon Black

              E           184.895      2  AC-30+SBS
              E
        F     E           160.300      2  AC-30+GTR-80
        F     E
        F     E           159.805      2  AC-30
        F
        F     G           151.275      2  AC-5+EVA
              G
              G           141.915      2  AC-5+SEBS

Force-Draft oven
Duncan Grouping              Mean      N  ASPHALT

              A            382.88      2  AC-30+EVA

              B            339.10      2  AC-30+Gilsonite
              B
        C     B            333.95      2  AC-30+SEBS
        C     B
        C     B            322.93      2  AC-20+SEBS
        C
        C     D            303.81      2  AC-20+EVA
              D
        E     D            278.75      2  AC-30+Carbon Black
        E     D
        E     D            270.98      2  AC-30+SBR
        E
        E                  261.10      2  AC-30
        E
        E     F            245.10      2  AC-30+GTR-80
              F
        G     F            219.09      2  AC-5+EVA
        G
        G                  201.87      2  AC-5+SEBS
```

7.4.2 Effects of Modifiers on Open-Graded Mixtures

Results of ANOVA on the indirect tensile strength for dense-graded mixture are shown in Table 7.8. The test results indicated that the forced-draft oven type produces the most severe rate of age-hardening on the measured tensile strength at 25°C (77°F). However, the forced-draft oven and natural roof 6-month aging process are not significantly different from the original no-aging condition at temperature of 5°C (41°F). Grouping of asphalt mixtures by exposure condition on the basis of indirect tensile strength at temperature of 25°C (77°F) for dense-graded mixtures are shown in Table 7.9.
As seen from table, the SEBS modifier increases the indirect tensile strength the most at temperature of 25°C (77°F), whereas the SBR modifier increases it the least. The results show that the mixtures containing EVA and SEBS modified AC-5 are not as stiff as the mixtures containing conventional AC-30 on the basis of indirect tensile strength.

7.4.3 Comparison Between Dense-Graded and Open-Graded Mixtures

All of indirect tensile strengths for both dense-graded and open-graded mixtures at temperature of 25°C (77°F) were plotted in bar charts. Figure 7.3 illustrates the comparison between dense-graded and open-graded mixtures before and after aging on the basis of indirect tensile strength at 25°C (77°F). As seen from this figure, all of the modified asphalt mixtures, with the exception of those containing EVA and SEBS modified AC-5 binders, have higher tensile strength than the

Table 7.8 Results of ANOVA and Duncan's grouping on the effect of exposure condition on indirect tensile strength

$$\text{Model} = \mu + A_i + E_j + (AE)_{ij} + \epsilon_{ijk}$$

Open-graded mixtures

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	36846.18670	7.16	0.0001
DURATION	2	403.06937	0.39	0.6789
ASPHALT*DURATION	20	9057.16933	0.88	0.6101

R-Square= 0.732

Duncan Grouping	Mean	N	EXPOSURE DURATION
A	290.849	22	No Aging
A	285.689	22	Roof Aging (6 months)
A	285.527	22	Force-Draft Oven (90 days)

TEMPERATURE=77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	32231.34233	37.79	0.0001
DURATION	2	38720.89028	227.00	0.0001
ASPHALT*DURATION	20	2275.82899	1.33	0.2258

R-Square= 0.974

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	190.650	22	Force-Draft Oven (90 days)
B	142.875	22	Roof Aging (6 months)
C	135.593	22	No Aging

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 7.8 Grouping of open-graded asphalt mixtures by exposure condition on the basis of indirect tensile strength at temperature of 77°F

```
No Aging
Duncan Grouping              Mean      N  ASPHALT

             A             168.640     2  AC-30+SEBS
             A
    B        A             163.205     2  AC-30+EVA
    B        A
    B        A    C        160.370     2  AC-30+Gilsonite
    B        A    C
    B   D    A    C        150.490     2  AC-30+GTR-80
    B   D         C
    B   D         C        146.250     2  AC-20+SEBS
        D         C
        D    E    C        141.025     2  AC-30+Carbon Black
        D    E
    F   D    E             132.100     2  AC-30+SBR
    F        E
    F        E             123.030     2  AC-30
    F
    F                      110.660     2  AC-20+EVA

             G              97.200     2  AC-5+SEBS
             G
             G              90.205     2  AC-5+EVA

Force-Draft oven
Duncan Grouping              Mean      N  ASPHALT
             A              226.82     2  AC-30+Gilsonite
             A
    B        A              216.37     2  AC-30+EVA
    B        A
    B        A    C         211.60     2  AC-30+SEBS
    B             C
    B        D    C         197.62     2  AC-20+SEBS
    B        D    C
    B        D    C         196.30     2  AC-30+Carbon Black
    B        D    C
    B        D    C         195.12     2  AC-20+GTR-80
             D    C
             D    C         188.35     2  AC-20+EVA
             D
             D              182.81     2  AC-30
             D
             D              180.87     2  AC-30+SBR

             E              157.17     2  AC-5+SEBS
             E
             E              130.06     2  AC-5+EVA
```

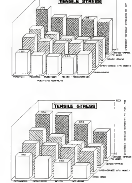


Figure 7.3 Comparison between dense-graded and open-graded mixture on the basis of tensile strength at 25°C (77°F)

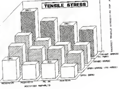


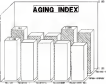
Figure 7-3 --Continued

conventional unmodified AC-30 asphalt mixtures. In addition, the tensile strength of open-graded mixtures is lower than that of dense-graded mixtures. The indirect tensile strength of open-graded unaged mixture is approximately 135 psi, whereas the unaged dense-graded mixtures has an indirect tensile strength up to 190 psi as seen from the statistical analysis. This is probably due to the high air void content of the open-graded mixtures. It is believed that a high air void content causes the mixtures to have higher deformation and lower strength. It can be seen that the mixtures containing modified AC-5 asphalts did not provide the same indirect tensile strength as the mixtures containing conventional AC-30 asphalt.

The rate of age-hardening of asphalt mixtures as evaluated by means of the ratios of indirect tensile strength at temperature of 25°C (77°F) before and after forced-draft oven aging process for both dense- and open-grade mixtures are shown in Table 7.10. All of the tensile strength ratios were plotted in bar charts. Figure 7.4 illustrates the comparison between dense-graded and open-graded mixtures on the basis of indirect tensile strength ratio. As seen from this figure, all of the modified dense-graded asphalt mixtures with the exception of SBR modified asphalt show slower rate of age-hardening than that of conventional unmodified AC-30 asphalt mixture. The SEBS modified AC-30 mixture shows the lowest aging index as compared with the others.

Table 7.10 Tensile strength ratio on the basis of force-draft oven for modified and unmodified asphalt concrete mixtures at temperature of 25°C (77°F)

Asphalt Blend	Dense-graded mixture (St ratio @ 77°F)	Open-graded mixture (St ratio @ 77°F)
AC-30+SBR	1.645	1.368
AC-16	1.635	1.486
AC-30+EVA	1.547	1.337
AC-30+GTR-80	1.528	1.256
AC-20+SEBS	1.515	1.351
AC-20+EVA	1.507	1.604
AC-5+EVA	1.452	1.550
AC-5+SEBS	1.417	1.815
AC-30+Gilsonite	1.455	1.414
AC-30+Carbon Black	1.355	1.383
AC-30+SEBS	1.285	1.255



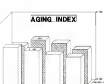


Figure 7.4 Comparison between dense-graded and open-graded mixture on the basis of tensile strength ratio at 25°C (77°F)

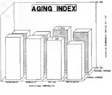


Figure 7.4-- Continued

The rate of age-hardening of the open-graded mixtures is slightly slower than that of dense-grade mixtures on the basis of the indirect tensile strength ratio. It appears that the aggregate plays an important role on the pavement age-hardening. In addition, all of the modified open-graded asphalt mixtures, with the exception of EVA modified AC-20, AC-5 and SEBS modified AC-5 asphalts, show slower rate of age-hardening than that of conventional unmodified AC-30 asphalt mixture at temperature of 25°C (77°F). Again, the SEBS modified AC-30 shows the lowest aging index than the others on the basis of strength ratio. All of these evidences indicate that the modifiers have the potential to slow down the rate of age-hardening of conventional asphalts. However, the forced-draft oven and the natural 6-month roof aging process did not cause a significantly higher indirect tensile strength at temperature of 5°C (41°F) for both dense- and open-graded modified asphalt mixtures.

7.5 Effects of Modifiers on Fracture Energy

The required energy to cause fracture of asphalt mixtures was evaluated by the fracture energy, which was determined by calculating the total area under the stress-strain curve from indirect tensile strength test. The typical stress-strain curve for original unaged modified and unmodified asphalt mixtures are displayed in Figure 7.5. Figure 7.6 shows the stress-strain relationship of open-graded and dense-graded

Dense-Graded Mixtures

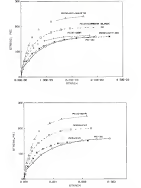


Figure 7.5 Stress-strain relationship of modified and unmodified asphalt mixtures at 25°C (77°F)

Dense-Graded Mixtures

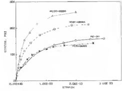


Figure 7.5 --Continued

Open-Graded Mixtures

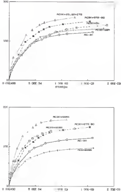


Figure 7.5 --Continued

Open-Graded Mixtures

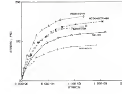


Figure 7.5 --Continued

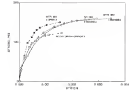


Figure 7.6 Stress-strain relationship of open- and dense-graded mixtures at 25°C (77°F)

mixtures at 25°C (77°F). Tabulated results in Appendixes D-3 and D-4 also display the fracture energy of dense-graded and open-graded mixtures. The results of ANOVA on the measured fracture energy at both 5° and 25°C (41° and 77°F) along with the Duncan's Multiple Range test results for dense-graded and open-graded mixtures are shown in Tables 7.11 and 7.12, respectively. The test results indicated that the fracture energy slightly increases after 6-month natural roof aging and then decrease after forced-draft oven aging for either dense-graded or open-graded mixture at both 5° and 25°C (41° and 77°F). This indicates that the fracture energy value tend to increase up to a maximum and then decrease as the asphalt hardens. All of fracture energy of different modified asphalt mixtures before and after force-draft oven aging were plotted in bar charts. Figures 7.7 and 7.8 illustrate the comparison between the dense-graded and open-graded mixtures before and after forced-draft oven aging on the basis of fracture energy at temperatures of 5°C (41°F) and 25°C (77°F), respectively. As seen from these figures, all of the unaged modified asphalt mixtures have higher fracture energy than that of mixtures containing the unmodified AC-30 for dense-graded mixture at 5°C (41°F). At temperature of 25°C (77°F), all of unaged modified asphalts, with the exception of SBR modified AC-30, EVA modified AC-20 ,EVA and SEBS modified AC-5 asphalt mixtures, show higher energy value than that of conventional unmodified AC-30 mixtures. However, all of modified asphalt

Table 7.11 Results of ANOVA and Duncan's grouping on the effects of exposure conditions on fracture energy

$$\text{Model} = \mu + A_i + E_j + (AE)_{ij} + \epsilon_{ijk}$$

Dense-graded mixtures

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	12053771.52	10.54	0.0001
DURATION	2	7045364.78	30.80	0.0001
ASPHALT*DURATION	20	3206544.85	1.40	0.1500

R-Square= 0.855

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	1750.5	22	Roof Aging(6 months)
A	1694.5	22	Original(No Aging)
B	1031.3	22	Force-Draft Oven (90 days)

TEMPERATURE= 77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	6545525.266	15.44	0.0001
DURATION	2	555544.104	6.66	0.0037
ASPHALT*DURATION	20	806872.743	0.50	0.5534

R-Square= 0.849

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	2007.51	22	Roof Aging(6 months)
A	1525.77	22	Original(No Aging)
B	1778.00	22	Force-Draft Oven (90 days)

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 7.12 Results of ANOVA and Duncan's grouping on the effects of exposure conditions on fracture energy

$$\text{Model} = \mu + A_i + B_j + (AB)_{ij} + \epsilon_{ijk}$$

Open-graded mixtures

TEMPERATURE=41°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	1103360.365	1.69	0.1250
DURATION	2	837176.843	6.41	0.0044
ASPHALT*DURATION	20	1416503.799	1.08	0.4072

R-Square= 0.609

Duncan Grouping	Mean	N	EXPOSURE DURATION
A	951.21	22	No Aging
A	922.44	22	Roof Aging (6 months)
B	699.21	22	Force-Draft Oven (90 days)

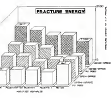
TEMPERATURE=77°F

Source	DF	Anova SS	F Value	Pr > F
ASPHALT	10	958153.1687	9.20	0.0001
DURATION	2	191211.9765	9.18	0.0007
ASPHALT*DURATION	20	260708.3438	1.25	0.2765

R-Square= 0.804

Duncan Grouping	Mean	N	EXPOSURE CONDITION
A	765.75	22	Roof Aging (6 months)
A	756.51	22	No Aging
B	647.23	22	Force-Draft Oven (90 days)

Note: Means with the same letter are not significantly different (Alpha= 0.05)



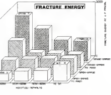


Figure 7.7 Comparison between dense-graded and open-graded mixture on the basis of fracture energy at 5°C (41°F)

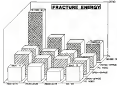


Figure 7.7--Continued

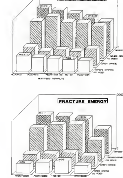


Figure 7.8 Comparison between dense-graded and open-graded mixtures on the basis of fracture energy at 25°C (77F)

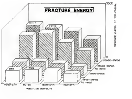


Figure 7-8 --Continued

mixtures decrease in fracture energy after force-draft oven aging, for either dense-graded or open-graded mixtures at both 5°C (41°F) and 25°C (77°F). This indicates that the addition of certain amount of modifiers could increase the fracture energy of conventional asphalt. However, from the standpoint of long-term aging characteristic, the addition of modifiers to conventional AC-30 tend to make the binders too brittle as seen from these figures. Results from statistical analysis by using ANOVA techniques along with Duncan's multiple range test also coincide with the trends observed from these figures. It is therefore concluded that the modified AC-30 binders are generally too hard, especially after they harden further under service. However, the modified AC-5 binders appear to be softer than the conventional AC-30 as seen from these analysis results.

7.6 Results of Rheology Tests on Recovered Asphalt Blends

The broken dense-graded and open-graded Marshall specimen from indirect tensile strength that were extracted by using the reflux extraction and rotovap recovery methods. The following conventional binder tests were performed on these recovered modified asphalt blends to evaluate the effects of different aging conditions on the rheological properties of these modified asphalt blends:

a. Penetration at 25°C (77°F)

b. Absolute viscosity at 60°C (140°F)

c. Infrared spectroscopy test

d. Schweyer rheometer test at 15° and 25°C (59° and 77°F).

Results of these conventional binder tests including penetration, absolute viscosity, constant power viscosity at two different temperatures, and carbonyl ratio from FTIR are tabulated in Appendix E. Scattering data were obtained due to the difficulty of recovery process on modified asphalts. It was observed that some of the modifiers are not soluble in toluene or trichloroethylene during the extraction process. It was found that only three of seven modifiers namely gilsonite, EVA, and EERS are recoverable. However, the available test results still indicate that the forced-draft oven aging process produces the most severe aging effects on the basis of the results of all binder tests.

7.7 Core Samples From Field Projects

Core samples were taken from two field projects, US-301 and Interstate Highway 75 in Hernando County in the State of Florida, periodically. Cores were extracted both from wheel path and from between wheel path. When extracting these core samples, it was observed that both Interstate highway I-75 and US-301 pavements are still in good condition after 8-year field service. There were not any measurable rutting and cracking observed at both the I-75 and US-301 projects. In addition, the measured average air voids from field cored samples for US-301 and I-75 projects are 14 percent and 5 percent, respectively. Indirect tensile strength test at 25°C (77°F) was performed on the core samples of asphalt concrete, and asphalt binders were recovered from the broken samples using the reflux and rotovap method. The recovered asphalt cements were subjected to penetration test at 25°C and absolute viscosity test at 60°C. Table 7.13 shows the indirect tensile strength of core samples from both I-75 and US-301 pavements. As seen from Table 7.13, the indirect tensile strength of WP samples are typically higher than that of BWP samples from the US-301 project. This observation is reasonable and expected because the WP is more densified by the traffic. However, the data from I-75 project do not show the same trend. This is probably due to the influence of the friction course is the I-75 project.

Results of penetration test at 25°C (77°F) and absolute viscosity at 60°C (140°F) are shown in Table 7.14. On the US-301 project, the results indicated that the WP samples produced higher viscosity and lower penetration than that of BWP samples after age-hardening. It could be explained by the fact that the imparted air (oxygen) during wheel path densification increases the rate of oxygen absorption in the asphalt and accelerates the age-hardening of the pavement material.

Table 7.13 Indirect tensile strength on cored samples at 25°C (77°F)

US 301

Duration (Years)	Type	Spec#	Heigh (inch)	Load (lbs)	Stress (psi)
8	BWP	01	0.984	709.23	114.71
	BWP	02	0.891	602.11	107.55
	BWP	03	1.000	687.26	109.38
	BWP	04	1.014	685.42	107.58
	WP	05	0.850	722.04	135.19
	WP	06	0.751	511.17	108.33
	WP	07	0.739	695.49	149.79
	WP	08	0.721	641.78	141.67
	WP	09	0.706	564.27	127.20

I-75

Duration (Years)	Type	Spec#	Heigh (inch)	Load (lbs)	Stress (psi)
8	BWP	01	1.691	1736.15	163.4
	BWP	02	1.687	1985.47	187.3
	BWP	03	1.694	1911.81	179.5
	BWP	04	1.671	1746.52	166.4
	WP	05	1.686	1630.86	153.9
	WP	06	1.893	1916.81	161.2
	WP	07	1.823	1783.45	155.9
	WP	08	1.812	1750.79	153.7
	SHOUDER	09	1.824	1562.19	136.3
	SHOUDER	10	1.719	2041.32	188.9
	SHOUDER	11	1.831	1955.26	169.9
	SHOUDER	12	1.852	2338.87	200.9

Table 7.14 Results of binder tests on samples from field project

US-301

TIME	SECT#	POSITION	PEN. (25°C)	VIS. (60°C)
ORI			73	2,246
PAVER	1		93	9,932
PAVER	2		38	7,980
3 MONTH	1	WP	36	15,998
	1	BWP	39	14,019
	2	WP	35	17,234
	2	BWP	38	10,165
1 YEAR	2	WP	39	10,732
	2	BWP	36	13,780
2 YEAR	1	WP	30	30,266
	1	BWP	30	29,932
	2	WP	30	22,127
	2	BWP	34	18,464
3 YEAR	1	WP	27	90,910
	1	BWP	27	46,350
	2	WP	26	38,316
	2	BWP	30	19,987
8 YEAR	1	WP	14	299,518
	1	BWP	16	170,632
	2	WP	17	87,642
	2	BWP	18	76,886

I-75

TIME	SECT#	POSITION	PEN. (25°C)	VIS. (60°C)
ORI			75	2,111
PAVER			47	10,416
10 DAY		WP	42	11,908
		BWP	42	10,030
3 MONTH		WP	37	12,650
		BWP	37	13,509
6 MONTH		WP	41	8,727
		BWP	34	14,061
1 YEAR		WP	39	8,939
		BWP	36	12,800
2 YEAR		WP	32	19,737
		BWP	28	29,669
3 YEAR		WP	30	20,658
		BWP	29	27,436
4 YEAR		WP	39	10,159
		BWP	36	12,912
8 YEAR		WP	37	6,301
		BWP	34	11,799
		SHOULDER	18	61,047

7.8 Summary of Findings

The major findings from the results of the mixture studies are summarized as follows:

1. The resilient modulus of asphalt mixtures at temperature of 25°C (77°F) appears to increase as the cycle frequency increases. However, at temperature of 5°C (41°F), the effect of test cycle frequency is not significant for either the unmodified or modified asphalt mixtures.
2. The rotation of specimen during the resilient modulus test appears to have a significant effect on the measured resilient modulus at both 5°C (41°F) and 25°C (77°F).
3. In terms of long-term aging effects, the forced-draft oven type produces the most severe rate of age-hardening on the basis of the measured total and instantaneous resilient modulus for both dense-graded and open-graded mixtures at temperature of 25°C (77°F). However, the natural 6-month roof aging process is not significantly different from that of the original no-aging condition.
4. From the standpoint of aging characteristics, the rate of age-hardening for open-graded mixtures is slower than that of dense-graded mixtures as measured by means of resilient modulus ratio and tensile strength ratio.

5. The fracture energy characterized by means of the area of stress-strain curve increases after 6-month natural roof aging and then decrease after force-draft oven aging for either dense-graded or open-graded mixtures at both 5°C (41°F) and 25°C (77°F).

6. On the basis of fracture energy, the addition of modifiers blending with conventional AC-30 tend to make the binders too brittle as they harden. However, modifiers blending with conventional AC-5 asphalt appear to be softer than that of conventional AC-30.

7. The modifiers of gilsonite, ethylene-vinyl-acetate (EVA) copolymer, and styrene-ethylene-butylene-styrene (SEBS) block copolymer are soluble in toluene and trichloroethylene.

8. All of the unaged modified asphalts, with the exception of SBR modified AC-30, EVA modified AC-20, EVA and SEBS modified AC-5 are superior to AC-30 on the basis of fracture energy.

9. The modified asphalt mixtures which are superior to AC-30 on the basis of resilient modulus ratio include (1) AC-30 + 5% GTR-80, (2) AC-30 + 5% SEBS, (3) AC-30 + 10% Carbon Black, (4) AC-30 + 5% EVA, and (5) AC-30 + 5% Gilsonite.

10. On the basis of indirect tensile strength ratio and resilient modulus ratio at temperature of 25°C, the

SEBS modified AC-30 mixture shows the lowest aging index than the others.

11. It appears that the combination of proper modified asphalt binders and proper aggregate type and gradation could slow down the age-hardening of the asphalt pavement.

CHAPTER 8
ANALYSIS AND DISCUSSIONS

8.1 Prediction of Long-Term Aging Characteristics of Asphalt Blends

In order to investigate the relationship between the laboratory-aged and the field-aged asphalt binder, an conventional AC-20 asphalt which was used in an actual paving project in Florida was used for comparison purpose. The sampled asphalt cement was aged by (a) the TFOT and RTFOT at the three different temperatures, (b) the California tilt oven test for 72 hours and 168 hours, (c) the SHRP standard PAV aging process at three different temperatures, and (d) the SHRP PAV for a duration of 40 hours Table 8.1 displays the rheological properties of laboratory-aged asphalt binder. The properties of these aged residues were compared with those of the recovered asphalt binders from field cored samples which were taken periodically from the pavement. The plot of penetration at 25°C (77°F) and absolute viscosity at 60°C (140°F) was used to investigate whether the laboratory-aged binders had similar characteristics as the field-aged binders. Figure 8.1 shows the pen-vis plots of the laboratory-aged AC-20 binders that was used in the actual paving project along with those of the field-aged binders that were recovered from cored samples at different ages. It can be seen that the

Table 8-1 Absolute viscosity and penetration of selected asphalt at different aging conditions

	Viscosity (poise)	Penetration (0.1 mm)
PAV@90°C	32,113	24
	35,161	23
PAV@100°C(20hrs)	80,894	21
	73,669	22
PAV@110°C	242,358	17
	219,362	17
PAV@100°C(30hrs)	188,903	17
	189,115	17
PAV@100°C(40hrs)	465,796	14
	491,866	14
California Tilt Oven @ 72hrs	91,409	18
	98,450	18
California Tilt Oven @168hrs	321,165	16
	322,382	16

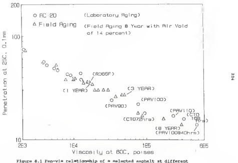


Figure 8.1 Pen-vis relationship of a selected asphalt at different long-term aging conditions

laboratory aged binders have similar aging characteristics as the field aged binders. As seen from Figure 8.1, the RTFOT aging process performed at temperature of 185°C (365°F) for 75 minutes can simulate a one-year field aging under typical Florida conditions. Also, the California tilt-oven process at temperature of 111°C (232°F) for a duration of 168 hours can simulate an eight-year field aging under the same conditions. In addition, it can also be observed that the standard SHRP PAV at the temperature of 90°C (194°F) for a duration of 20 hours can simulate a three-year field aging under the same conditions. It is noted that the standard PAV at temperature of 100°C (212°F) for a duration of 40 hours can predict more than eight-year field aging under typical Florida conditions. The same concept was used to curve-fit the pen-vis relationship for modified asphalts. Figure 8.2 shows the pen-vis relationship of gilsonite modified asphalt binder after different TFOT and RTFOT processes and the recovered binders from gilsonite modified asphalt mixtures after different aging processes. As seen from Figure 8.2, the laboratory natural 6-months roof aging process produces similar aging effects to that of RTFOT at temperature of 185°C (365°F). In addition, the forced-draft oven produced much more severe aging effects than that of RTFOT at 196°C (385°F). Similar pen-vis plots for different modified asphalts are shown in Appendix F.1.

The relationship between carbonyl ratio and absolute viscosity at 60°C (140°F) was investigated by plotting the log

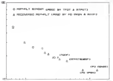


Figure 8.2 Pen-vis relationship of gilsonite modified asphalt binders at different long-term aging conditions

of carbonyl ratio versus the log of viscosity. Figure 8.3 shows the carbonyl ratio versus absolute viscosity plot for a conventional AC-30 asphalt binder at different laboratory aging conditions. As seen from Figure 8.3, the laboratory aged binder has similar characteristics as that of the recovered binders from the asphalt mixtures since they all fall on the same curve. It can be seen that the changes in molecular structure of the asphalts in terms of functional groups due to high temperature TFOT aging process are similar to the mixtures that are aged at low oven temperature of 60°C (140°F). The same approach was also employed on the modified asphalts. Figure 8.4 shows the relationship between carbonyl ratio and 60°C viscosity for a gilsonite modified asphalt at different aging conditions. Similar plots for other modified asphalts are shown in appendixes F.2. It can be observed that the plots show similar trends. However, greater variations of data from a neat relationship were observed for these modified asphalts.

8.2 Evaluation of Fatigue Characteristics of Modified Asphalt Mixtures

The total resilient modulus at 25 °C (77 °F) were plotted against the corresponding total resilient modulus at 5°C (41°F) to evaluate their relationships. Figure 8.5 shows the relationship between the total resilient modulus at 5°C and that at 25°C for both dense-graded and open-graded mixtures. The relationship can be defined by the linear equation

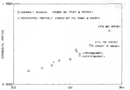


Figure 8.3 Relationship between carbonyl ratio and viscosity at 60°C for conventional AC-30 at different aging conditions.

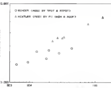


Figure 8.4 Relationship between carbonyl ratio and absolute viscosity for gilsonite modified asphalt at different aging conditions

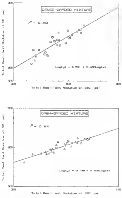


Figure 8.5 Relationship between total resilient modulus at 5°C and that of 25°C

$$\text{Log}(\text{Mr@5C}) = \beta_0 + \beta_1\text{Log}(\text{Mr@25C}) \qquad (8.2)$$

where

Mr@5C = total resilient modulus at 5°C, psi

Mr@25C = total resilient modulus at 25°C, psi

Results of regression analysis indicate that the total resilient modulus at 25°C (77°F) has a good correlation with the total resilient modulus at 5°C (41°F). R^2 values of 0.80 and 0.84 were obtained for both dense-graded and open-graded mixtures, respectively. This relationship indicates that the data at temperature of 25°C (77°F) could be adequately considered as predictors of low temperature data. A similar linear model was used to best-fit the relationship between the indirect tensile strength and total resilient modulus at 25°C (77°F) for both dense-graded and open-graded modified and unmodified asphalt concrete mixtures. The relationships between these two properties are shown in Figure 8.6. The equation used was of the following form:

$$\text{Log}(\text{Mr}) = \beta_0 + \beta_1\text{Log}(\text{St}) \qquad (8.2)$$

where

Mr = total resilient modulus at 25°C (77°F), psi

St = indirect tensile strength at 25°C (77°F), psi

As seen from Figure 8.6, the best fitted equation gave a linear relationship with an R^2 value of 0.88 for dense-graded mixtures and 0.83 for open-graded mixtures. In general, the total resilient modulus increases with an increase of indirect tensile strength at 25°C (77°F). In addition, the relationship

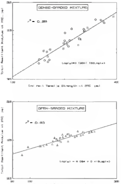


Figure 8.6 Relationship between total resilient modulus and indirect tensile strength at 25°C

does not vary with different types of mixtures. The absolute viscosity at 60°C (140°F) was plotted against the corresponding total resilient modulus and indirect tensile strength at 25°C (77°F) to evaluate their possible relationships, in Figures 8.7 and 8.8, respectively. Poor correlation was obtained between absolute viscosity at 60°C and indirect tensile strength and total resilient modulus at 25°C. It is therefore concluded that the data at 25°C (77°F) cannot be considered as predictors of high temperature properties. As seen from these analysis, it is reasonable to conclude that the modified asphalt mixtures have a linear elastic behavior within the low temperature range of 5° to 25°C (41 to 77°F).

The total resilient modulus at 25°C (77°F) was plotted against the corresponding fracture energy at 25°C, which are characterized by means of the area under the stress-strain curve. Figure 8.9 shows the relationship between total resilient modulus and fracture energy at 25°C. As seen from Figure 8.9, the total resilient modulus had poor relationship with the fracture energy. However, a general trend can still be observed from this plot. The fracture energy increases as the total resilient modulus increases until the resilient modulus reaches a maximum around 8E5 psi for dense-graded mixtures and 5E5 psi for open-graded mixtures. As the total resilient modulus increases beyond that point, the fracture energy values tend to decrease. It is, therefore, concluded

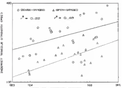


Figure 6.7 Relationship between absolute viscosity and indirect tensile strength

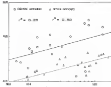


Figure 8.8 Relationship between absolut viscosity and total resilient modulus

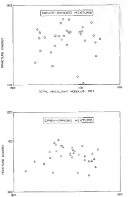


Figure 8.9 Relationship between total resilient modulus and fracture energy at 25°C

that the resilient modulus test does not provide a good indication of low temperature fracture energy.

9.3 Evaluation of Current Specifications for Modified Asphalts

An asphalt binder can age during the mixing and compaction process as well as during long-term service. The specification criteria in a true performance specification should ensure that the binder would perform as it ages in actual service. The current test procedures of the Thin-Film Oven Test (ASTM D-1754) and the Rolling-Thin-Film Oven Test (ASTM D-2872) have been considered adequate for simulating the aging of binders that occurs during mixing and compaction of hot asphalt mixtures. However, the long-term field aging is still not addressed in the current asphalt specifications.

Results of the tests on the modified asphalt binders presented in this study indicate that the TFOT and/or RTFOT procedure could be run at high process temperature to simulate the long-term aging that occurs in the field. However, the TFOT or RTFOT at a high process temperature such as 185°C (365°F) can simulate field aging in the early stages of the pavement life only. It has been suggested [82] that the kinetics of aging is completely governed by the state of dispersion of the polar, reactive molecules in the asphalt, and that the kinetics of oxidative age-hardening at high temperatures is different from that at the pavement service temperatures.

It has been shown in this study that the California tilt-oven process at the temperature of 111°C (231°F) for a duration of 168 hours can predict an eight-year asphalt age-hardening in the field under typical Florida conditions.

New laboratory aging procedures using the pressure aging vessel (PAV) has been adopted by the SHRP binder specifications recently. In this test procedure, the asphalt residue after the standard RTFOT process are further aged in a pressure air vessel at a pressure of 300 psi (2 MPa) and a temperature of 90°C to 110°C (194 to 230°F) for 20 hours to simulate long-term field exposure. Results of the tests obtained from this study indicate that the PAV aging process at a temperature of 100°C (212°F) for a duration of 40 hours can simulate a field aging of over 8 years under typical Florida conditions.

The Strategic Highway Research Program (SHRP) [94] proposed two aging procedures to evaluate both the short-term and long-term aging characteristics of unmodified or modified asphalt mixtures. The selected aging process for short-term aging is to place loose mixtures in a forced draft oven for about six hours at a temperature of 135°C (275°F) to simulate the aging that occurs during mixing and compaction. The proposed procedure for long-term aging is to place compacted mixture samples in a forced-draft oven at a temperature of 60°C (140°F) for a duration of 7 days to simulate long-term field aging conditions.

8.4 Selection of Suitable Modified Asphalts for Long-Term Performance

The concern with conventional asphalt binders has been that they tend to increase in hardness with aging along with reduced flexibility. Through the addition of modifiers, it is possible to select modified asphalt binders which do not increase the rate of age-hardening, but yet impart the desired flexibility after aging. Results of the tests on the modified asphalt binders presented in this study indicate that modifiers added to AC-20 or AC-30 asphalts tend to have slower rate of age-hardening than that of the modified AC-5 asphalts on the basis of viscosity ratio and penetration retained. However, in the case of modified asphalt blends containing high-viscosity asphalt such as AC-30, the binders are too stiff and brittle. It is believed that modification of compatible low-viscosity asphalt will yield not only satisfactory results at a particular high and low service temperature, but also slower rate of age-hardening.

Generally speaking, the modifiers which appear to impart elastic property as well as anti-aging effect to the conventional asphalts are fine ground tire rubber passing #80 sieve (GTR-80) and block copolymer styrene-ethylene-butylene-styrene (SEBS). However, it should be pointed out that the appropriate selection of asphalt grade, modifier type, and modifier concentration along with the consideration of required traffic and environmental condition of the pavement is very important in order to obtain benefits from using modified asphalts.

It should be noted that the aggregates comprise approximately 95 percent of asphalt mixtures, and thus they play a major role in the mixture design process. Generally speaking, the texture of the aggregate is important, and it is desirable to have a rough texture for improved rutting resistance, particularly in the thicker asphalt bound layers. Available evidence indicates that dense-graded aggregate gradations are desirable to mitigate the effects of rutting and also to improve the fatigue performance in thicker section of asphalt concrete. On the other hand, for thin sections of asphalt concrete, fatigue response would appear to be improved by applying a more open-graded aggregate gradation.

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The analysis and evaluation of the effects of asphalt types, modifier types, modifier concentration, and mixture types investigated in this study have indicated that all of above factors can significantly affect the asphalt pavement performance. The following conclusions were derived from the results obtained in this study:

1 The asphalt binders which were artificially aged in the laboratory by the TFOT, RTFOT, California tilt oven and SHRP pressure aging vessel appear to have similar rheological properties as those which were aged under field conditions.

2. The RTFOT aging process performed at a temperature of 185°C (365°F) for 75 minutes appear to simulate a one-year field aging effect under typical Florida conditions.

3. The SHRP pressure aging vessel (PAV) at 90 °C (194 °F) for a standard duration of 20 hours appears to simulate an three-year field aging effect under typical Florida conditions. In addition, the PAV at 100 °C (212 °F) for a duration of 40 hours could simulate an aging effect of over 8 years of service under typical Florida conditions.

4. The California tilt oven process at 111°C for a duration of 168 hours appear to simulate an eight-year field aging effect under typical Florida conditions.
5. The RTFOT is a more severe aging process than the TFOT at any of the three process temperature as seen from the percent penetration retained and absolute viscosity ratio of the aged modified asphalts.
6. The RTFOT was not suitable for use on the coarse ground tire rubber modified asphalts because the modified asphalt binders spilled out from the bottle during the RTFOT process.
7. Since the diametral resilient moduli at 25 °C (77 °F) had a good correlation with the moduli at 5 °C (41 °F), it appears reasonable that the data at 25°C could be considered as predictor of the corresponding low temperature data.
8. Different mixture types appear to have different aging characteristics as evidenced by the difference between the open and dense graded mixtures used in this study.
9. The resilient modulus at 25 °C (77 °F) had a good correlation with the indirect tensile strength at 25 °C (77 °F). In general, the resilient modulus increases with an increase in indirect tensile strength at a particular loading rate. In addition,

this relationship does not vary with different types of mixtures.

10. The modified asphalts which are superior to AC-30 on the basis of aging characteristics include (1) AC-20 + 3.5% SEBS, (2) AC-30 + 5% SEBS, and (3) AC-30 + 5% GTR-80.
11. All of the unaged modified asphalts, with the exception of SBR modified AC-30, EVA modified AC-20, EVA and SEBS modified AC-5 are superior to AC-30 on the basis of fracture energy.
12. The modified asphalt mixtures which are superior to AC-30 asphalt mixture on the basis of resilient modulus ratio include (1) AC-30 + 5% GTR-80, (2) AC-30 + 5% SEBS, (3) AC-30 + 10% Carbon Black, (4) AC-30 + 5% EVA, and (5) AC-30 + 5% Gilsonite.
13. On the basis of indirect tensile strength ratio and resilient modulus ratio at temperature of 25°C, the SEBS modified AC-30 mixture shows the lowest aging index than the others.
14. The addition of modifiers to conventional AC-30 asphalt tend to make the binders too brittle as they age-hardens. However, modified AC-5 asphalt appear to be softer at low temperatures than that of conventional AC-30.

9.2 Recommendations

On the basis of the findings in this study, the following recommendations are suggested:

1. Since most asphalt blends exhibit non-newtonian behavior, either at low temperatures or high service temperatures, where the shear stress is not directly proportional to the strain rate, additional research should be done by using Schweyer rheometer and/or rotational cylindric viscometer to evaluate the shear susceptibility of modified asphalts or aged asphalts.
2. Comparison of results from the Schweyer rheometer test and the new SHRP bending beam rheometer test should be made to evaluate the low-temperature characteristics of aged asphalts and modified asphalts.
3. Additional research is needed to evaluate the new SHRP proposed dynamic shear rheometer (DSR) test for characterizing the viscoelastic behavior of modified asphalts at intermediate temperatures between 25°C and 60°C, since the dynamic measurement is particularly useful in the transition region where the delayed elastic response is dominant. Also, additional research could be conducted to develop the relationship between Schweyer rheometer and the dynamic shear rheometer test results.

4. Additional research should be conducted to evaluate the effects of using different duration times in the SHRP proposed PAV aging process, since the PAV for 40 hours has been shown to simulate field aging of more than 8 years under typical Florida conditions.

5. Further investigation on age hardening of modified asphalts using the California tilt oven aging process should be continued to evaluate the aging characteristics of modified asphalts, since the California tilt oven could simulate a 8-year-old field pavement aging under typical Florida conditions.

6. Additional research should be conducted to investigate the difference between TFOT and RTFOT treatment prior to the PAV aging process.

7. Additional investigation should be conducted on the mixing temperature of modified asphalts since this study indicates that the mixing temperature plays an important role on the long-term pavement cracking performance.

8. Homogeneity of asphalt blends has always been a problem for modified asphalt research study as it affects the variability of the data generated. It is recommended that a physical test such as softening point test should be performed right after asphalt blending to evaluate the reproducibility of the data

which is related to the homogeneity of the asphalt blends.

9. The forced-draft oven has been found to be a good device to simulate long-term field aging effect. However, duration of 90 days seems to be impractical for routine testing purpose. Modification of forced-draft oven through the application of low pressure air and flow rate adjustment could be considered to accelerate the aging process of mixtures within short periods of time.
10. Stiffer mixtures appear to be more susceptible to cracking at low temperatures. However, the resilient modulus test results showed that the changes in resilient modulus at 5°C and 25°C are mainly a function of the changes in elastic deformation. Since recoverable deformations do not lead to thermal cracking, resilient modulus should not be a good indicator of cracking potential at low temperature. The stress-strain response provides a better measurement of performance of the mixture. Additional research is needed on stress-strain response of modified asphalt mixtures.
11. Since aggregates comprise approximately 95 percent of most asphalt mixtures, they play a major role in the mixture design process. Additional research is needed to investigate the effects of different

mixture type and aggregate gradations on modified asphalt pavement performance.

12. Gyratory testing machine (GTM) could be considered for fabrication of asphalt specimens since the GTM method provides more evaluation parameters than that of the Marshall method.
13. The softer asphalt such as AC-10 or AC-15 should be used in modified asphalts since AC-30 modified asphalts are too brittle as they hardens.
14 Higher modifier contents are recommended in AC-5 modified asphalts since the modified AC-5 asphalt used in this study are not stiff enough under typical Florida conditions.
15. A skin film tends to form on the surface of the modified asphalt sample during TFOT test. Modification of the TFOT should be studied to eliminate this problem.
16. In order to evaluate the rutting resistance of the modified asphalts, selected asphalt blends should be evaluated by wheel tracking simulation tests

APPENDIX A

PROPERTIES OF MARSHALL SPECIMEN

Table A.1 Density and air void of dense-graded Marshall specimens

A (AC-30)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A01	1119.7	607.2	1121.3	2.178	135.91	6.06	2.516
A02	1122.5	609.6	1123.6	2.184	136.27	5.81	2.533
A03	1123.8	610.6	1126.2	2.180	136.01	5.99	2.536
A04	1128.2	610.9	1130.1	2.173	135.59	6.28	2.525
A05	1131.4	613.1	1133.4	2.175	135.69	6.21	2.554
A06	1125.3	609.2	1128.1	2.169	135.32	6.46	2.537
A07	1125.3	610.4	1126.9	2.179	135.95	6.03	2.538
A08	1123.5	608.4	1126.2	2.170	135.39	6.42	2.543
A09	1122.3	606.9	1124.0	2.170	135.43	6.39	2.541
A10	1118.8	604.4	1120.2	2.169	135.35	6.45	2.544
A11	1123.5	606.4	1125.3	2.165	135.11	6.61	2.550
A12	1127.2	611.3	1129.3	2.176	135.79	6.14	2.554
A13	1122.7	607.2	1124.5	2.170	135.43	6.39	2.556
A14	1124.5	608.3	1126.5	2.170	135.41	6.40	2.549
A15	1120.6	603.4	1122.4	2.159	134.73	6.87	2.555
A16	1131.3	611.7	1133.5	2.168	135.29	6.49	2.563
A17	1123.1	607.0	1124.7	2.169	135.37	6.43	2.534
A18	1128.8	609.6	1130.4	2.167	135.25	6.52	2.566
A19	1127.6	612.6	1129.4	2.182	136.15	5.89	2.542
A20	1125.2	610.0	1126.8	2.177	135.86	6.09	2.545
			Avg :	2.173	135.56	6.30	
			Var :	0.0000	0.1387	0.0662	
			Std :	0.0060	0.3724	0.2574	

Asphalt Content: 6.5%
Theoretical Maximum Specific Gravity: 2.3150
2.3220

Table A.1 --Continued

A10C (AC30+10% CARBON BLACK)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A10C01	1120.1	611.3	1122.1	2.193	136.83	4.74	2.533
A10C02	1120.1	611.3	1122.3	2.192	136.78	4.78	2.531
A10C03	1124.7	608.6	1126.8	2.170	135.43	5.72	2.535
A10C04	1116.3	607.9	1119.7	2.161	136.10	5.25	2.550
A10C05	1124.2	606.5	1127.0	2.160	134.77	6.16	2.543
A10C06	1125.2	606.3	1127.9	2.157	134.61	6.29	2.520
A10C07	1124.8	608.3	1127.2	2.168	135.26	5.64	2.537
A10C08	1121.2	605.7	1122.7	2.169	135.32	5.79	2.539
A10C09	1125.1	611.0	1127.1	2.180	136.03	5.30	2.517
A10C10	1130.0	613.3	1132.0	2.179	135.94	5.36	2.538
A10C11	1131.2	614.8	1134.3	2.177	135.87	5.41	2.559
A10C12	1134.4	616.3	1135.9	2.183	136.23	5.16	2.540
A10C13	1120.3	603.7	1122.7	2.159	134.70	6.23	2.500
A10C14	1124.7	607.7	1126.4	2.168	135.30	5.61	2.562
A10C15	1127.5	609.7	1129.4	2.170	135.38	5.75	2.527
A10C16	1128.4	609.9	1129.7	2.171	135.46	5.70	2.547
A10C17	1124.6	606.9	1125.9	2.167	135.21	5.87	2.526
A10C18	1124.9	606.0	1126.3	2.170	135.43	5.72	2.547
A10C19	1122.5	606.2	1123.9	2.177	135.82	5.45	2.550
A10C20	1121.3	606.0	1122.8	2.178	135.92	5.38	2.552
			Avg :	2.173	135.62	5.59	
			Var :	0.0001	0.3559	0.1725	
			Std :	0.0096	0.5965	0.4153	

Asphalt Content: 6.5%

Theoretical Maximum Specific Gravity: 2.3040

2.3000

Table A.1—Continued

ASG (AC30+5% GILSONITE)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A5G01	1122.1	608.8	1123.7	2.179	135.99	5.38	2.518
A5G02	1124.0	609.1	1125.4	2.177	135.85	5.47	2.526
A5G03	1122.7	610.1	1125.0	2.180	136.06	5.32	2.521
A5G04	1123.9	606.2	1125.9	2.163	134.95	6.10	2.552
A5G05	1122.7	608.4	1124.9	2.174	135.64	5.62	2.541
A5G06	1119.6	605.6	1121.6	2.170	135.39	5.79	2.521
A5G07	1121.9	604.5	1124.2	2.159	134.71	6.27	2.538
A5G08	1126.9	609.5	1128.8	2.170	135.41	5.78	2.541
A5G09	1123.8	610.6	1125.2	2.184	136.27	5.18	2.519
A5G10	1122.0	604.0	1124.2	2.157	134.59	6.35	2.543
A5G11	1126.4	611.9	1128.5	2.180	136.06	5.33	2.556
A5G12	1122.2	607.4	1124.3	2.171	135.47	5.73	2.539
A5G13	1126.4	617.0	1128.1	2.204	137.52	4.31	2.500
A5G14	1133.8	615.0	1136.2	2.175	135.74	5.54	2.558
A5G15	1126.2	613.6	1127.4	2.192	136.77	4.83	2.526
A5G16	1125.1	607.0	1127.2	2.163	134.96	6.09	2.551
A5G17	1120.9	608.8	1122.4	2.182	136.18	5.24	2.527
A5G18	1125.9	609.3	1127.5	2.173	135.58	5.66	2.548
A5G19	1130.2	610.6	1131.9	2.168	135.29	5.86	2.552
A5G20	1129.0	609.0	1130.6	2.164	135.06	6.02	2.556
			Avg :	2.174	135.67	5.59	
			Var :	0.0001	0.4774	0.2312	
			Std :	0.0111	0.6909	0.4808	

Asphalt Content: 6.5%

Theoretical Maximum Specific Gravity: 2.3045

2.3016

Table A.1--Continued

A5R8 (AC30+5% GTR80)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A5R801	1119.8	602.1	1121.5	2.156	134.53	3.18	2.548
A5R802	1116.0	600.8	1117.8	2.159	134.70	3.06	2.540
A5R803	1124.3	603.4	1126.8	2.148	134.04	3.53	2.567
A5R804	1127.7	601.0	1132.3	2.123	132.45	4.68	2.594
A5R805	1127.4	602.3	1129.6	2.138	133.42	3.98	2.593
A5R806	1127.1	601.6	1128.6	2.139	133.46	3.95	2.582
A5R807	1123.4	600.1	1124.9	2.141	133.58	3.86	2.576
A5R808	1134.0	600.5	1135.7	2.119	132.22	4.84	2.596
A5R809	1131.5	601.1	1134.8	2.120	132.29	4.78	2.612
A5R810	1123.3	598.1	1126.0	2.128	132.78	4.44	2.576
A5R811	1120.0	601.0	1121.7	2.151	134.22	3.40	2.525
A5R812	1122.0	602.7	1123.8	2.153	134.36	3.30	2.555
A5R813	1128.1	601.4	1130.0	2.134	133.17	4.16	2.590
A5R814	1126.2	601.5	1128.5	2.137	133.35	4.03	2.584
A5R815	1121.6	601.9	1123.0	2.152	134.31	3.34	2.559
A5R816	1123.4	599.3	1127.8	2.126	132.64	4.54	2.576
A5R817	1127.0	603.1	1128.3	2.146	133.90	3.63	2.576
A5R818	1119.7	595.3	1121.4	2.128	132.81	4.42	2.578
A5R819	1139.5	605.6	1141.4	2.127	132.71	4.49	2.612
A5R820	1120.2	597.9	1121.5	2.139	133.50	3.92	2.570
			Avg :	2.138	133.42	3.97	
			Var :	0.0001	0.5727	0.2967	
			Std :	0.0121	0.7568	0.5447	

Asphalt Content: 6.5%

Theoretical Maximum Specific Gravity: 2.2268
2.2265

Table A.1 —Continued

A15R4 (AC30+15% GTR40)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air (%)	Ht (in)
A15R41	1128.4	569.0	1135.2	1.993	124.38	12.65	2.715
A15R42	1107.0	576.0	1110.3	2.072	129.28	9.19	2.809
A15R43	1125.8	580.9	1128.9	2.054	128.19	9.96	2.676
A15R44	1126.5	584.7	1129.1	2.069	129.12	9.31	2.871
A15R45	1122.7	582.3	1126.4	2.063	128.78	9.58	2.882
A15R46	1128.8	587.3	1131.5	2.074	129.43	9.09	2.653
A15R47	1134.4	569.4	1142.5	1.979	123.52	13.24	2.749
A15R48	1122.1	581.4	1125.9	2.061	128.59	9.68	2.883
A15R49	1133.2	561.0	1145.0	1.940	121.06	14.95	2.789
A15R410	1128.2	583.2	1130.5	2.058	128.40	9.81	2.681
A15R411	1130.8	573.9	1136.8	2.009	125.35	11.95	2.708
A15R412	1124.6	568.5	1131.2	1.999	124.71	12.40	2.891
A15R413	1107.7	565.2	1113.4	2.020	126.06	11.45	2.847
A15R414	1126.3	578.4	1131.5	2.036	127.07	10.75	2.687
A15R415	1124.0	568.9	1133.3	1.991	124.27	12.71	2.702
A15R416	1139.3	583.8	1146.5	2.025	126.34	11.26	2.701
A15R417	1120.6	567.0	1128.9	1.994	124.44	12.59	2.684
A15R418	1129.3	572.0	1136.8	1.999	124.77	12.37	2.712
A15R419	1128.0	559.9	1136.9	1.952	121.77	14.47	2.765
A15R420	1135.8	566.5	1146.8	1.957	122.13	14.22	2.781
			Avg :	2.017	125.88	11.58	
			Var :	0.0017	6.6553	3.2834	
			Std .	0.0413	2.5798	1.8120	

Asphalt Content: 7.0%

Theoretical Maximum Specific Gravity: 2.2810

2.2822

Table A.1 --Continued

A35SR (AC30+3.5% SBR)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A35SR01	1118.7	601.9	1120.5	2.157	134.61	5.79	2.548
A35SR02	1117.5	601.1	1119.2	2.157	134.59	5.80	2.547
A35SR03	1123.5	604.7	1125.1	2.159	134.72	5.71	2.557
A35SR04	1125.9	608.2	1127.4	2.169	135.32	5.29	2.553
A35SR05	1120.9	603.4	1122.7	2.158	134.69	5.73	2.554
A35SR06	1127.9	607.2	1130.9	2.154	134.39	5.94	2.567
A35SR07	1114.2	601.0	1116.6	2.161	134.84	5.62	2.536
A35SR08	1125.2	606.2	1127.0	2.161	134.82	5.64	2.561
A35SR09	1121.0	602.1	1122.9	2.152	134.31	5.99	2.545
A35SR10	1122.9	604.1	1124.8	2.157	134.57	5.81	2.561
A35SR11	1133.7	612.7	1135.4	2.169	135.34	5.27	2.569
A35SR12	1136.8	614.1	1139.4	2.164	135.04	5.48	2.580
A35SR13	1120.0	605.5	1122.4	2.167	135.21	5.37	2.545
A35SR14	1120.3	604.8	1122.0	2.166	135.16	5.40	2.542
A35SR15	1114.4	599.8	1116.7	2.156	134.53	5.84	2.542
A35SR16	1122.2	607.4	1124.3	2.171	135.47	5.18	2.538
A35SR17	1123.9	606.8	1126.7	2.162	134.89	5.59	2.553
A35SR18	1130.6	607.1	1133.9	2.146	133.92	6.27	2.584
A35SR19	1117.7	601.1	1120.3	2.153	134.33	5.98	2.535
A35SR20	1120.5	603.0	1123.8	2.151	134.25	6.03	2.558
			Avg :	2.159	134.75	5.69	
			Var :	0.0000	0.1625	0.0796	
			Std :	0.0065	0.4031	0.2821	

Asphalt Content: 6.5%
Theoretical Maximum Specific Gravity: 2.2898
2.2895

Table A.1 --Continued

A5E (AC30+5%EVA)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A5E01	1118.6	606.4	1121.1	2.173	135.61	4.68	2.523
A5E02	1121.5	607.8	1123.9	2.173	135.60	4.69	2.535
A5E03	1125.4	612.7	1127.8	2.185	136.33	4.17	2.530
A5E04	1117.6	603.6	1120.0	2.164	135.01	5.11	2.534
A5E05	1125.5	610.7	1127.6	2.177	135.87	4.50	2.533
A5E06	1125.9	610.9	1127.1	2.181	136.10	4.34	2.524
A5E07	1126.9	611.3	1129.2	2.176	135.78	4.57	2.535
A5E08	1122.3	606.3	1124.3	2.167	135.20	4.97	2.543
A5E09	1129.5	607.7	1131.1	2.158	134.66	5.35	2.571
A5E10	1135.4	615.1	1137.3	2.174	135.67	4.64	2.561
A5E11	1129.4	607.1	1131.6	2.153	134.37	5.56	2.577
A5E12	1128.5	608.5	1130.7	2.161	134.85	5.22	2.563
A5E13	1126.5	609.7	1128.4	2.172	135.52	4.75	2.549
A5E14	1128.1	607.4	1130.5	2.157	134.57	5.41	2.567
A5E15	1124.8	606.6	1128.0	2.157	134.61	5.38	2.552
A5E16	1128.4	608.8	1132.0	2.157	134.58	5.41	2.564
A5E17	1118.2	605.0	1121.6	2.165	135.07	5.06	2.519
A5E18	1128.2	614.3	1130.1	2.187	136.49	4.07	2.529
A5E19	1138.4	615.3	1140.5	2.168	135.26	4.93	2.579
A5E20	1121.8	606.3	1124.7	2.164	135.03	5.09	2.536
			Avg :	2.168	135.31	4.89	
			Var :	0.0001	0.3639	0.1798	
			Std :	0.0097	0.6032	0.4240	

Asphalt Content:	6.5%
Theoretical Maximum Specific Gravity:	2.3420 2.2180

Table A.1 --Continued

B5E (AC20+5% EVA)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
B5E01	1126.1	607.5	1128.6	2.161	134.65	5.31	2.556
B5E02	1116.5	603.6	1119.9	2.167	135.23	5.04	2.541
B5E03	1128.0	606.8	1129.5	2.158	134.66	5.44	2.567
B5E04	1123.7	605.2	1125.2	2.161	134.84	5.31	2.560
B5E05	1123.6	606.0	1125.4	2.163	134.99	5.21	2.551
B5E06	1127.2	604.6	1130.9	2.142	133.64	6.16	2.578
B5E07	1129.6	607.3	1132.1	2.152	134.31	5.69	2.567
B5E08	1127.6	606.4	1129.6	2.155	134.48	5.57	2.567
B5E09	1128.6	607.3	1131.1	2.154	134.42	5.61	2.571
B5E10	1128.6	611.2	1130.5	2.173	135.61	4.77	2.551
B5E11	1122.8	604.8	1124.5	2.160	134.81	5.34	2.550
B5E12	1124.2	607.2	1126.3	2.166	135.14	5.11	2.530
			Avg	2.159	134.750	5.280	
			Var :	0.0001	0.2341	0.1154	
			Std	0.0078	0.4838	0.3397	

Asphalt Content.	6.8%
Theoretical Maximum Specific Gravity	2.2887
	2.2758

Table A.1--Continued

A5SE (AC30+5%SEBS)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
A5SE01	1126.5	606.7	1128.3	2.160	134.77	5.05	2.5483
A5SE02	1119.2	603.1	1121.6	2.159	134.69	5.10	2.5360
A5SE03	1128.9	609.5	1130.9	2.165	135.10	4.81	2.5560
A5SE04	1126.4	602.8	1131.8	2.133	133.10	6.22	2.5865
A5SE05	1126.7	606.7	1130.4	2.164	135.00	4.68	2.5505
A5SE06	1125.2	603.6	1127.9	2.147	133.97	5.61	2.5663
A5SE07	1123.9	602.9	1125.3	2.151	134.25	5.41	2.5603
A5SE08	1115.9	598.5	1119.0	2.144	133.78	5.74	2.5453
A5SE09	1125.3	605.8	1127.8	2.156	134.52	5.22	2.5623
A5SE10	1113.3	592.7	1115.7	2.129	132.63	6.41	2.5613
A5SE11	1114.0	600.4	1116.6	2.156	134.66	5.12	2.5255
A5SE12	1127.3	604.8	1129.9	2.147	133.96	5.61	2.5525
A5SE13	1129.0	605.9	1131.6	2.148	134.01	5.56	2.5710
A5SE14	1129.3	606.5	1132.5	2.147	133.97	5.61	2.5735
A5SE15	1127.2	605.8	1130.8	2.147	133.96	5.60	2.5608
A5SE16	1124.5	605.3	1127.6	2.152	134.29	5.36	2.5513
A5SE17	1120.5	599.2	1123.9	2.136	133.26	6.11	2.5463
A5SE18	1129.0	606.7	1132.3	2.146	134.04	5.56	2.5705
A5SE19	1129.2	604.4	1132.7	2.137	133.36	6.03	2.5643
A5SE20	1125.4	603.2	1128.7	2.142	133.63	5.84	2.5708
			Avg :	2.148	134.06	5.54	
			Var :	0.0001	0.3691	0.1632	
			Std :	0.0097	0.6075	0.4280	

Asphalt Content: 6.5%
Theoretical Maximum Specific Gravity: 2.2760
2.2710

Table A.1 --Continued

B35SE (AC20+3.5% SEBS)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
B5SE01	1128.3	606.3	1131.6	2.148	134.03	5.19	2.5690
B5SE02	1123.6	603.0	1125.4	2.151	134.21	5.06	2.5608
B5SE03	1127.2	607.8	1129.1	2.162	134.93	4.56	2.5508
B5SE04	1126.2	607.0	1128.3	2.160	134.81	4.64	2.5523
B5SE05	1129.0	605.7	1131.3	2.148	134.04	5.19	2.5690
B5SE06	1130.8	609.8	1132.9	2.162	134.89	4.58	2.5623
B5SE07	1117.7	603.1	1119.9	2.163	134.95	4.54	2.5308
B5SE08	1128.5	605.7	1130.9	2.149	134.08	5.16	2.5748
B5SE09	1127.9	605.1	1130.8	2.146	133.88	5.30	2.5718
B5SE10	1124.5	605.0	1126.7	2.155	134.50	4.86	2.5510
B5SE11	1129.2	607.9	1131.7	2.156	134.52	4.84	2.5638
B5SE12	1125.3	607.7	1127.3	2.166	135.14	4.41	2.5508
			Avg	2.155	134.498	4.859	
			Var	0.0000	0.1771	0.0886	
			Std	0.0067	0.4209	0.2977	

Asphalt Content: 6.5%

Theoretical Maximum Specific Gravity: 2.2600

2.2710

Table A.1--Continued

C35SE (AC5+3.5% SEBS)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
C35SE01	1116.5	600.1	1117.9	2.156	134.55	5.03	2.5303
C35SE02	1125.3	605.4	1126.9	2.159	134.79	4.69	2.5463
C35SE03	1127.3	605.7	1128.9	2.156	134.55	5.03	2.5556
C35SE04	1126.5	604.6	1127.6	2.153	134.35	5.17	2.5490
C35SE05	1128.0	606.4	1129.5	2.156	134.56	5.03	2.5500
C35SE06	1126.3	603.0	1127.6	2.147	133.97	5.44	2.5650
C35SE07	1124.5	604.0	1125.4	2.157	134.56	5.01	2.5495
C35SE08	1122.6	602.5	1125.0	2.149	134.09	5.36	2.5556
C35SE09	1129.4	610.3	1130.9	2.169	135.37	4.45	2.5453
C35SE10	1129.2	607.0	1130.8	2.156	134.52	5.05	2.5583
C35SE11	1130.6	609.0	1132.1	2.161	134.67	4.61	2.5543
C35SE12	1129.0	612.6	1130.9	2.176	135.92	4.06	2.5110
			Avg .	2.156	134.674	4.944	
			Var :	0.0001	0.2590	0.1290	
			Std :	0.0062	0.5089	0.3592	

Asphalt Content: 6.5%

Theoretical Maximum Specific Gravity: 2.2660

2.2750

Table A.1 --Continued

C5E (AC5+ 5% EVA)

	Wt in air (g)	Wt in water (g)	Wt SSD (g)	SG	Unit Wt (pcf)	Air Void (%)	Ht (in)
C5E01	1124.9	609.1	1126.6	2.174	135.64	4.83	2.5315
C5E02	1123.8	607.2	1125.8	2.167	135.22	5.12	2.5328
C5E03	1129.1	612.3	1130.6	2.178	135.94	4.62	2.5348
C5E04	1124.9	605.3	1126.8	2.157	134.60	5.56	2.5375
C5E05	1125.8	607.7	1127.0	2.168	135.28	5.08	2.5430
C5E06	1127.2	608.5	1128.7	2.167	135.21	5.13	2.5425
C5E07	1128.8	609.3	1130.0	2.168	135.27	5.09	2.5490
C5E08	1127.3	608.7	1128.8	2.167	135.25	5.10	2.5448
C5E09	1129.2	610.0	1130.4	2.170	135.40	5.00	2.5523
C5E10	1129.6	609.3	1131.1	2.165	135.08	5.22	2.5578
C5E11	1127.4	611.5	1128.5	2.181	136.07	4.52	2.5428
C5E12	1123.3	605.3	1124.8	2.162	134.93	5.33	2.5443
			Avg :	2.169	135.324	5.050	
			Var :	0.0000	0.1513	0.0745	
			Std :	0.0062	0.3890	3.2729	

Asphalt Content 6.5%

Theoretical Maximum Specific Gravity. 2.2880

2.2800

Table A.2 Density and air void of open-graded Marshall specimens

A (AC-30)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A01	940.7	2.4525	3.9965	1.866	116.43	18.92
A02	938.3	2.5340	4.0030	1.795	112.04	19.10
A03	943.5	2.5588	3.9980	1.792	111.84	19.24
A04	944.8	2.5548	3.9950	1.800	112.34	18.88
A05	938.3	2.7078	4.0000	1.683	105.00	24.18
A06	944.9	2.5330	3.9965	1.815	113.24	18.23
A07	938.0	2.5153	3.9945	1.816	113.31	18.18
A08	936.9	2.5373	3.9960	1.797	112.12	19.04
A09	945.1	2.5375	3.9970	1.811	113.03	18.38
A10	941.5	2.5460	3.9940	1.801	112.39	18.84
A11	945.7	2.5035	4.0080	1.827	114.01	17.67
A12	941.8	2.5350	3.9990	1.805	112.63	18.67
A13	937.7	2.5350	3.9960	1.800	112.31	18.90
A14	939.9	2.5223	3.9970	1.812	113.09	18.34
A15	937.4	2.4910	4.0070	1.821	113.63	17.94
A16	938.5	2.5213	3.9955	1.812	113.05	18.37
A17	939.8	2.5293	3.9940	1.810	112.93	18.45
A18	933.9	2.5538	3.9950	1.780	111.09	19.78
A19	937.8	2.5203	3.9970	1.809	112.90	18.48
A20	937.9	2.5220	3.9970	1.809	112.86	18.50
			Avg :	1.803	112.51	18.75
			Var :	0.0010	4.0361	2.1046
			Std :	0.0322	2.0090	1.4507

Asphalt Content:	6.3%
Theoretical Maximum Specific Gravity:	2.2232 2.2154

Table A.2 --Continued

A10C (AC30+10% CARBON BLACK)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A10C01	939.8	2.5519	3.9920	1.795	112.04	19.83
A10C02	938.2	2.5223	3.9930	1.813	113.11	19.06
A10C03	938.9	2.5223	3.9970	1.810	112.97	19.16
A10C04	938.9	2.5119	3.9970	1.818	113.45	18.82
A10C05	935.3	2.5220	3.9915	1.809	112.86	19.24
A10C06	938.8	2.5315	3.9940	1.808	112.71	19.35
A10C07	942.6	2.5370	3.9945	1.809	112.90	19.22
A10C08	943.8	2.5340	3.9960	1.812	113.06	19.09
A10C09	949.2	2.9340	3.9985	1.815	113.23	18.98
A10C10	934.8	2.9288	3.9970	1.799	112.27	19.66
A10C11	940.6	2.5253	3.9985	1.812	113.06	19.09
A10C12	949.5	2.5230	3.9929	1.834	114.47	18.09
A10C13	937.5	2.5220	3.9920	1.812	113.09	19.07
A10C14	943.1	2.4828	4.0075	1.838	114.87	17.94
A10C15	943.2	2.5535	3.9925	1.800	112.35	19.81
A10C16	942.2	2.5325	3.9940	1.812	113.08	19.09
A10C17	944.6	2.5305	3.9970	1.815	113.27	18.95
A10C18	940.1	2.5053	3.9920	1.830	114.16	18.31
A10C19	937.9	2.5188	4.0085	1.802	112.47	19.52
A10C20	945.0	2.5240	4.0090	1.814	113.17	19.02
			Avg.	1.813	113.12	19.05
			Var.	0.0001	0.4347	0.2228
			Std	0.0108	0.6593	0.4718

Asphalt Content	6.3%
Theoretical Maximum Specific Gravity:	2.2368 2.2423

Table A.2 --Continued

A5G (AC30+5% GILSONITE)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A5G01	930.7	2.4778	3.9935	1.830	114.19	17.69
A5G02	932.8	2.4808	3.9940	1.831	114.28	17.62
A5G03	937.3	2.4960	3.9970	1.826	113.96	17.85
A5G04	933.7	2.5013	3.9970	1.815	113.28	18.34
A5G05	940.6	2.5048	3.9945	1.829	114.10	17.75
A5G06	942.3	2.5195	3.9950	1.821	113.61	18.10
A5G07	940.9	2.4938	3.9965	1.835	114.53	17.44
A5G08	940.6	2.5283	3.9960	1.810	112.96	18.57
A5G09	941.2	2.5393	3.9935	1.806	112.68	18.77
A5G10	940.5	2.5273	3.9960	1.811	112.99	18.55
A5G11	939.9	2.5323	3.9985	1.804	112.56	18.86
A5G12	937.8	2.5068	3.9965	1.820	113.56	18.14
A5G13	942.5	2.5058	3.9985	1.828	114.06	17.78
A5G14	944.4	2.5093	4.0075	1.821	113.62	18.10
A5G15	937.8	2.5170	3.9930	1.816	113.30	18.33
A5G16	941.7	2.5285	3.9965	1.812	113.05	18.51
A5G17	943.6	2.4888	4.0060	1.836	114.54	17.43
A5G18	939.7	2.5133	4.0045	1.812	113.04	18.51
A5G19	944.2	2.5408	3.9905	1.813	113.14	18.44
A5G20	939.8	2.5328	3.9955	1.806	112.69	18.77
			Avg :	1.819	113.51	18.18
			Var :	0.0001	0.3774	0.1961
			Std :	0.0098	0.6143	0.4429

Asphalt Content: 6.3%
Theoretical Maximum Specific Gravity: 2.2282
2.2181

Table A.2 --Continued

A5R8 (AC30+5% GTR80)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A5R801	939.3	2.4370	4.0000	1.872	116.79	15.88
A5R802	941.2	2.3543	4.0080	1.934	120.66	13.10
A5R803	942.5	2.4363	3.9990	1.880	117.28	15.53
A5R804	939.5	2.4535	4.0000	1.860	116.03	16.43
A5R805	944.9	2.4553	3.9980	1.871	116.73	15.93
A5R806	943.3	2.4583	3.9965	1.867	116.48	16.11
A5R807	947.8	2.4555	3.9910	1.883	117.49	15.38
A5R808	945.3	2.4635	4.0030	1.861	116.10	16.38
A5R809	943.6	2.4780	3.9930	1.856	115.79	16.60
A5R810	944.0	2.4603	3.9915	1.871	116.76	15.90
A5R811	944.8	2.4648	4.0040	1.858	115.92	16.51
A5R812	941.7	2.4735	3.9865	1.861	116.15	16.35
A5R813	947.6	2.4825	3.9975	1.856	115.81	16.59
A5R814	951.1	2.4770	3.9980	1.866	116.47	16.12
A5R815	944.6	2.4518	4.0020	1.869	116.63	16.00
A5R816	941.7	2.4623	3.9865	1.870	116.68	15.97
A5R817	940.4	2.4800	3.9940	1.847	115.25	16.99
A5R818	944.2	2.4713	3.9860	1.868	116.59	16.03
A5R819	942.6	2.4720	3.9905	1.861	116.10	16.38
A5R820	948.0	2.4663	3.9915	1.875	116.97	15.75
			Avg :	1.869	116.63	16.00
			Var :	0.0003	1.1278	0.5850
			Std :	0.0170	1.0620	0.7649

Asphalt Content. 6.3%
Theoretical Maximum Specific Gravity: 2.2215
2.2286

Table A.2 --Continued

A15R4 (AC30+15% GTR40)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A15R41	941.4	2.5628	3.9950	1.788	111.59	19.93
A15R42	942.1	2.5333	3.9945	1.811	113.00	19.92
A15R43	939.5	2.5135	3.9935	1.819	113.51	19.55
A15R44	943.1	2.5525	4.0075	1.788	111.54	19.97
A15R45	939.7	2.5943	3.9970	1.777	110.96	20.46
A15R46	942.9	2.5975	4.0050	1.779	111.01	20.35
A15R47	942.7	2.5458	4.0030	1.796	112.04	19.61
A15R48	940.3	2.5550	3.9975	1.789	111.66	19.88
A15R49	944.1	2.5753	4.0025	1.779	110.95	20.39
A15R410	939.0	2.5473	4.0145	1.775	110.79	20.52
A15R411	943.2	2.5375	4.0040	1.801	112.41	19.35
A15R412	938.8	2.5775	4.0050	1.764	110.09	21.01
A15R413	942.5	2.5728	4.0020	1.777	110.90	20.43
A15R414	947.6	2.5895	4.0085	1.770	110.42	20.77
A15R415	946.0	2.6130	4.0120	1.749	109.05	21.76
A15R416	943.7	2.5775	4.0145	1.765	110.15	20.97
A15R417	943.4	2.5430	4.0070	1.795	112.02	19.92
A15R418	946.6	2.5878	4.0025	1.774	110.70	20.57
A15R419	939.0	2.5990	4.0095	1.764	110.05	21.04
A15R420	939.2	2.6218	4.0195	1.723	107.50	22.87
			Avg :	1.779	111.01	20.35
			Var :	0.0004	1.7261	0.8886
			Std :	0.0211	1.3139	0.9427

Asphalt Content: 6.3%
Theoretical Maximum Specific Gravity: 2.2390
2.2310

Table A.2 --Continued

A35SR (AC30+3.5% SBR)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A35SR01	934.2	2.4570	4.0035	1.843	115.01	17.07
A35SR02	937.0	2.4688	3.9950	1.848	115.30	16.86
A35SR03	942.0	2.4843	4.0030	1.839	114.73	17.27
A35SR04	942.6	2.4405	3.9955	1.880	117.30	15.42
A35SR05	937.8	2.4623	3.9955	1.854	115.67	16.59
A35SR06	940.5	2.4565	3.9925	1.866	116.45	16.03
A35SR07	942.2	2.5018	3.9980	1.831	114.23	17.63
A35SR08	944.6	2.5335	3.9940	1.816	113.32	18.29
A35SR09	944.3	2.4958	3.9985	1.839	114.74	17.27
A35SR10	945.5	2.4718	3.9950	1.862	116.20	16.21
A35SR11	940.4	2.4963	3.9990	1.830	114.21	17.65
A35SR12	942.3	2.5153	3.9945	1.824	113.83	17.92
A35SR13	942.5	2.5100	3.9915	1.831	114.27	17.60
A35SR14	940.4	2.5065	3.9890	1.832	114.32	17.57
A35SR15	942.1	2.5178	3.9900	1.826	113.95	17.83
A35SR16	943.0	2.5113	3.9940	1.829	114.13	17.71
A35SR17	939.4	2.5158	3.9980	1.815	113.26	18.33
A35SR18	936.5	2.5358	3.9985	1.795	111.99	19.25
A35SR19	944.7	2.5320	3.9935	1.818	113.43	18.21
A35SR20	945.2	2.5153	4.0055	1.820	113.56	18.12
			Avg :	1.835	114.50	17.44
			Var :	0.0004	1.4646	0.7615
			Std :	0.0194	1.2102	0.8726

Asphalt Content	6.3%
Theoretical Maximum Specific Gravity:	2.2230 2.2220

Table A.2--Continued

A5E (AC30+5%EVA)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A5E01	937.6	2.4773	3.9915	1.846	115.18	17.21
A5E02	936.3	2.4735	3.9940	1.844	115.05	17.30
A5E03	942.2	2.4308	3.9960	1.886	117.69	15.40
A5E04	943.0	2.5088	3.9910	1.834	114.41	17.76
A5E05	937.0	2.4745	3.9950	1.843	115.03	17.32
A5E06	940.9	2.4790	4.0000	1.843	115.01	17.33
A5E07	941.5	2.5013	3.9860	1.841	114.86	17.44
A5E08	940.0	2.5010	3.9915	1.833	114.38	17.79
A5E09	942.0	2.5073	3.9910	1.833	114.36	17.80
A5E10	944.1	2.5268	4.0020	1.813	113.11	18.70
A5E11	943.2	2.5308	3.9895	1.819	113.53	18.40
A5E12	944.8	2.5213	3.9540	1.825	113.89	18.13
A5E13	941.6	2.5453	3.9890	1.806	112.72	18.98
A5E14	936.5	2.5067	3.9910	1.822	113.72	18.26
A5E15	942.4	2.5318	3.9920	1.815	113.24	18.60
A5E16	945.4	2.5425	3.9905	1.814	113.21	18.62
A5E17	936.2	2.5230	3.9905	1.811	112.98	18.79
A5E18	935.7	2.5233	3.9515	1.808	112.85	18.89
A5E19	946.3	2.5210	3.9920	1.830	114.20	17.91
A5E20	942.9	2.5320	3.9915	1.816	113.32	18.54
			Avg :	1.829	114.14	17.96
			Var :	0.0003	1.2902	0.6666
			Std :	0.0182	1.1359	0.8164

Asphalt Content: 6.3%
Theoretical Maximum Specific Gravity: 2.2300
2.2290

Table A.2 --Continued

A5SE (AC30+5%SEBS)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
A5SE01	938.0	2.4893	3.9965	1.833	114.38	17.87
A5SE02	939.2	2.5260	3.9965	1.809	112.86	18.96
A5SE03	943.5	2.5223	3.9925	1.823	113.78	18.31
A5SE04	941.7	2.5155	3.9920	1.825	113.89	18.22
A5SE05	944.6	2.5575	3.9940	1.799	112.26	19.40
A5SE06	943.4	2.5253	3.9935	1.820	113.57	18.46
A5SE07	944.7	2.5533	3.9935	1.803	112.48	19.24
A5SE08	943.8	2.5400	3.9920	1.812	113.05	18.83
A5SE09	942.8	2.5185	4.0015	1.817	113.35	18.61
A5SE10	942.9	2.5163	4.0055	1.815	113.24	18.70
A5SE11	943.6	2.5153	3.9955	1.826	113.93	18.20
A5SE12	944.9	2.5518	3.9930	1.804	112.60	19.15
A5SE13	945.4	2.5445	3.9915	1.812	113.07	18.82
A5SE14	941.0	2.5278	3.9895	1.817	113.40	18.58
A5SE15	941.9	2.5243	3.9880	1.823	113.75	18.33
A5SE16	945.8	2.5393	3.9945	1.814	113.18	18.74
A5SE17	942.2	2.5265	3.9905	1.820	113.54	18.48
A5SE18	940.0	2.5255	3.9925	1.814	113.21	18.72
A5SE19	937.4	2.5278	3.9895	1.810	112.96	18.89
A5SE20	942.1	2.5388	3.9880	1.813	113.12	18.78
			Avg. :	1.815	113.28	18.66
			Var :	0.0001	0.2612	0.1346
			Std :	0.0082	0.5110	0.3669

Asphalt Content: 6.3%
Theoretical Maximum Specific Gravity: 2.2360
2.2280

Table A.2 --Continued

B5E (AC20+5%EVA)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
B5E01	943.7	2.4995	3.9850	1.847	115.27	17.37
B5E02	941.5	2.5095	4.0040	1.818	113.46	18.67
B5E03	943.2	2.5093	3.9685	1.854	115.72	17.05
B5E04	941.9	2.5373	3.9900	1.812	113.05	18.98
B5E05	942.0	2.5135	3.9950	1.825	113.85	18.39
B5E06	943.5	2.5203	3.9935	1.822	113.69	18.50
B5E07	938.7	2.4705	3.9885	1.852	115.58	17.17
B5E08	931.0	2.4753	3.9850	1.840	114.83	17.69
B5E09	939.1	2.4775	4.0045	1.837	114.60	17.85
B5E10	949.9	2.5213	3.9855	1.843	115.00	17.57
B5E11	941.7	2.4775	3.9950	1.850	115.47	17.23
B5E12	943.3	2.4900	3.9985	1.843	115.00	17.57
			Avg :	1.837	114.824	17.835
			Var :	0.000	0.733	0.377
			Std :	0.0137	0.8562	0.6138

Asphalt Content. 6.3%

Theoretical Maximum Specific Gravity. 2.2387

2.2326

Table A.2 --Continued

C5E (AC5+5%EVA)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
C5E01	945.3	2.5113	3.9950	1.842	114.92	17.21
C5E02	940.1	2.4510	3.9875	1.852	115.54	16.77
C5E03	543.5	2.4976	3.5505	1.843	115.02	17.15
C5E04	546.9	2.5150	3.5525	1.835	114.52	17.51
C5E05	541.2	2.4510	3.5900	1.844	115.07	17.11
C5E06	944.4	2.4510	3.9950	1.846	115.17	17.03
C5E07	935.3	2.4460	4.0065	1.851	115.49	16.80
C5E08	536.7	2.4903	3.5505	1.843	114.58	17.17
C5E09	540.9	2.4558	4.0010	1.830	114.17	17.76
C5E10	940.8	2.5015	3.9890	1.836	114.59	17.45
C5E11	541.4	2.4540	3.5505	1.842	114.93	17.21
C5E12	941.5	2.4949	3.9520	1.848	115.33	16.52
			Avg	1.843	114.577	17.174
			Var	0.000	0.148	0.077
			Std	0.0062	0.3844	0.2769

Asphalt Content: 6.3%

Theoretical Maximum Specific Gravity: 2.2287

2.2206

Table A.2 --Continued

B35SE (AC20+3.5%SEBS)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
B5SE01	945.9	2.5245	3.9960	1.823	113.77	18.54
B5SE02	941.0	2.5060	4.0020	1.822	113.67	18.61
B5SE03	946.2	2.5158	3.9940	1.832	114.31	18.16
B5SE04	946.4	2.4875	3.9930	1.854	115.69	17.17
B5SE05	941.8	2.5495	3.9995	1.794	111.97	19.83
B5SE06	942.3	2.5110	3.9960	1.826	113.94	18.42
B5SE07	939.2	2.5150	3.9975	1.816	113.30	18.88
B5SE08	937.8	2.5500	3.9930	1.792	111.83	19.93
B5SE09	943.5	2.5283	3.9910	1.820	113.59	18.67
B5SE10	943.7	2.5388	3.9985	1.806	112.72	19.29
B5SE11	941.6	2.5160	3.9980	1.819	113.52	18.72
B5SE12	944.2	2.5468	3.9960	1.804	112.57	19.40
			Avg :	1.817	113.407	18.802
			Var :	0.000	1.026	0.526
			Std :	0.0162	1.0131	0.7254

Asphalt Content: 6.3%

Theoretical Maximum Specific Gravity: 2.2390

2.2375

Table A.2--Continued

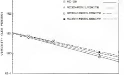
C5SE (AC5+3.5%SEBS)

	Wt in air (g)	Height (in)	Diameter (in)	SG	Unit Wt (pcf)	Air Void (%)
C5SE01	942.6	2.5058	3.9935	1.833	114.36	18.33
C5SE02	945.6	2.5033	3.9975	1.837	114.61	18.15
C5SE03	944.6	2.5470	3.9950	1.805	112.66	19.54
C5SE04	942.2	2.5340	3.9940	1.811	113.01	19.29
C5SE05	945.6	2.5423	3.9995	1.807	112.74	19.49
C5SE06	940.6	2.5258	3.9995	1.809	112.87	19.39
C5SE07	937.7	2.5360	3.9970	1.798	112.21	19.86
C5SE08	935.2	2.4983	4.0001	1.818	113.43	19.00
C5SE09	946.6	2.5328	3.9975	1.817	113.39	19.02
C5SE10	945.2	2.5258	3.9970	1.820	113.57	18.90
C5SE11	944.6	2.5410	3.9975	1.807	112.79	19.45
C5SE12	942.8	2.5323	3.9965	1.811	113.02	19.29
			Avg :	1.814	113.220	19.143
			Var :	0.000	0.447	0.228
			Std :	0.0107	0.6687	0.4776

Asphalt Content: 6.3%
Theoretical Maximum Specific Gravity: 2.2463
2.2417

APPENDIX E

RESULTS OF CONSISTENCY AND RHEOLOGY TESTS

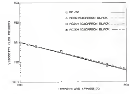


Regression Equation

AC-30 : LogLog(Vis)= 19.696 - 6.923Log(Temp) R^2= 0.9912
AC-30 +5% Gilsonite
: LogLog(Vis)= 18.938 - 6.632Log(Temp) R^2= 0.9931
AC-30 +10% Gilsonite
: LogLog(Vis)= 17.515 - 6.099Log(Temp) R^2= 0.9912
AC-30 +15% Gilsonite
: LogLog(Vis)= 16.465 - 5.710Log(Temp) R^2= 0.9869

Note: Viscosity in Poise
Temperature in °F+459.7

Figure B.1 Relationship between viscosity and temperature for different ModifiedAsphalts.



Regression Equation

AC-30: LogLog(Vis)= 19.696 - 6.923Log(Temp) R^2= 0.9912

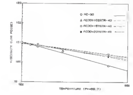
AC-30 +5% Carbon Black
LogLog(Vis)= 19.187 - 6.737Log(Temp) R^2= 0.9911

AC-30 +10% Carbon Black
LogLog(Vis)= 18.859 - 6.617Log(Temp) R^2= 0.9887

AC-30 +15% Carbon Black
LogLog(Vis)= 18.473 - 6.471Log(Temp) R^2= 0.9921

Note: Viscosity in Poise
Temperature in °F+459.7

Figure B.1--Continued



Regression Equation

AC-30: LogLog(Vis)= 19.696 - **6.923**Log(Temp) R^2= 0.9912

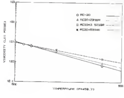
AC-30 +10% GTR-40
: LogLog(Vis)= 13.627 - **4.699**Log(Temp) R^2= 0.9977

AC-30 +15% GTR-40
: LogLog(Vis)= 13.592 - **4.659**Log(Temp) R^2= 0.9906

AC-30 +20% GTR-40
: LogLog(Vis)= 11.856 - **4.023**Log(Temp) R^2= 0.9876

Note: Viscosity in Poise
Temperature in °F+459.7

Figure 8.1--Continued

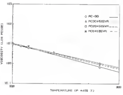


Regression Equation

AC-30: LogLog(Vis)= 19.696 - 6.923Log(Temp) R^2= 0.9912
AC-30 +2% SBR
LogLog(Vis)= 17.734 - 6.198Log(Temp) R^2= 0.9922
AC-30 +3.5% SBR
: LogLog(Vis)= 13.983 - 4.820Log(Temp) R^2= 0.9996
AC-30 +5% SBR
: LogLog(Vis)= 14.001 - 4.827Log(Temp) R^2= 0.9970

Note: Viscosity in Poise
Temperature in °F+459.7

Figure B.1--Continued

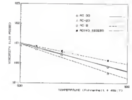


Regression Equation

AC-30 : LogLog(Vis)= 19.696 − **6.923**Log(Temp) R^2= 0.9912
AC-30 +5% EVA
: LogLog(Vis)= 16.645 − **5.794**Log(Temp) R^2= 0.9998
AC-20 +5% EVA
: LogLog(Vis)= 17.492 − **6.098**Log(Temp) R^2= 0.9959
AC-5 +5% EVA
: LogLog(Vis)= 17.436 − **6.100**Log(Temp) R^2= 0.9998

Note: Viscosity in Poise
Temperature in °F+459.7

Figure B.1--Continued

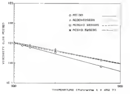


Regression Equation

AC-30: LogLog(Vis)= 19.696 - 6.923Log(Temp) R^2= 0.9912
AC-20
: LogLog(Vis)= 16.923 - 6.651Log(Temp) R^2= 0.9672
AC-5
: LogLog(Vis)= 23.757 - 6.460Log(Temp) R^2= 0.9732
AC-5 +3.5% SEBS
: LogLog(Vis)= 14.690 - 5.674Log(Temp) R^2= 0.9963

Note: Viscosity in Poise
Temperature in °F+459.7

Figure B-1--Continued



Regression Equation

AC-30: LogLog(Vis)= 19.696 - **6.923**Log(Temp) R^2= 0.9912
AC-30 +5% SEBS
: LogLog(Vis)= 15.249 - **5.261**Log(Temp) R^2= 0.9872
AC-20 +3.5% SEBS
: LogLog(Vis)= 14.829 - **5.199**Log(Temp) R^2= 0.9874
AC-5 +3.5% SEBS
: LogLog(Vis)= 14.690 - **5.974**Log(Temp) R^2= 0.9983

Note: Viscosity in Poise
Temperature in °F+459.7

Figure B.1--Continued

Table 8.2— TFOT Effect on Penetration, Kinematic Viscosity and PVN

	PENETRATION			KIN. VISCOSITY (CST)			PVN	
	ORI	TFOT	RET(%)	ORI	TFOT	RATIO	ORI	TFOT
AC-30	59	41	69.5	440	591	1.34	-0.60	-0.61
A5G	48	26	32.1	812	1328	1.63	-0.41	-0.40
A10G	28	19	67.9	991	1418	1.43	-0.31	-0.24
A15G	20	14	70.0	1450	2348	1.62	-0.18	0.07
A3C	63	35	55.6	468	708	1.51	-0.50	-0.53
A10C	88	34	38.7	488	1023	2.10	-0.49	-0.08
A13C	50	34	68.0	562	937	1.67	-0.48	+0.19
A2R8	54	39	72.2	550	813	1.48	-0.44	-0.24
A3R8	52	40	76.9	1019	1460	1.43	0.37	0.55
A8R8	46	35	76.1	1492	2115	1.42	0.74	0.88
A10R4	43	27	80.0	16468 *3221	42338 *7212	2.57 2.24	3.92 *1.74	4.27 *2.18
A15R4	30	26	86.7	35404 *4153	83290 *14327	2.35 3.45	4.88 *1.89	5.09 *2.89
A20R4	29	26	89.7	7947 *12383	15801 *23384	1.99 1.89	2.31 *2.87	3.29 *3.49
A25R	52	35	67.3	734	843	1.15	-0.08	-0.30
A33SR	50	35	70.0	2802	3285	1.17	1.70	1.44
A5ER	47	32	68.1	2889	3405	1.18	1.33	1.38
A5B	46	36	78.3	1162	1603	1.38	0.43	0.53
A5SB	33	24	72.7	2383	2921	1.23	0.96	0.86

* : is based on Haake viscometer.

** : the meaning for the codes for the binders can be found in Table 4.2

Table B.2-- Continued

	PENETRATION			KIN. VISCOSITY (CST)			PVN	
	ORI	TFOT	RET(%)	ORI	TFOT	RATIO	ORI	TFOT
B	60	44	72.3	453	604	1.22	-0.59	-0.51
B10C	55	43	78.2	540	1171	2.17	-0.44	0.34
B5C	38	20	70.9	642	827	1.29	-0.67	-0.47
B5RS	52	26	69.2	716	1047	1.46	-0.11	0.01
B15R4	44	20	68.2	*7046	*7797	1.10	*2.76	*2.24
B35SR	52	38	71.7	1215	1272	1.05	0.62	0.21
B3E	59	41	69.5	762	1125	1.47	0.11	0.24
B5E	62	22	50.8	972	1268	1.30	0.52	0.12
B8E	44	27	84.1	2302	2197	1.29	1.27	1.48
B25SE	42	21	72.8	2660	3493	1.31	1.55	1.52
C	127	76	59.8	235	215	1.52	-0.99	-0.88
C5E	76	48	62.2	765	1028	1.24	0.42	0.29
C35SE	62	41	66.1	2257	2462	1.04	1.71	1.27

* is based on Haake viscometer

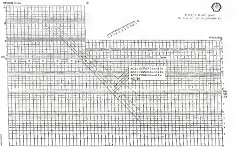


Figure B.3 Viscosity and Penetration vs. Temperature for conventional Asphalt Compare to Gilsonite Modified Asphalts

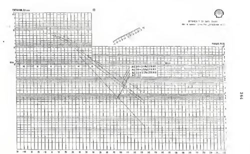


Figure B.3 --Continued

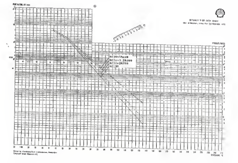


Figure B.3 --Continued

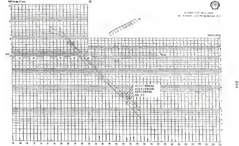


Figure B.3 —Continued

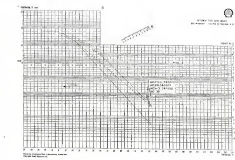


Figure B.1 —Continued

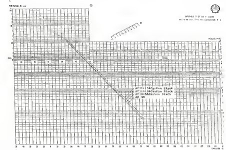


Figure B-3—Continued

Table 8.4 TFOT Effects on Absolute Viscosity and kinematic viscosities

	ABS. VISCOSITY (POISE) @ 60°C		HARDENING	KIN. VISCOSITY (CST) @ 135°C		TEMPERATURE SUSCEPTIBILITY (60 °C TO 135°C)	
	ORI	TFOT	INDEX	ORI	TFOT	ORI	TFOT
A	3034	6303	2.04	440	591	3.557	3.597
A5G	6323	18008	2.85	613	1000	3.587	3.597
A10G	15416	39864	2.59	991	1418	3.551	3.631
A15C	38131	95509	2.51	1450	2348	3.598	3.573
A5C	3928	8013	3.74	468	786	3.473	3.636
A10C	3295	10685	3.24	488	1835	3.478	3.364
A15C	4438	19952	4.50	563	937	3.474	3.636
A2R8	4235	8131	1.93	550	813	3.513	3.460
A5R8	6437	13081	1.88	1019	1468	3.317	3.196
A8R8	8970	17752	1.98	1493	3115	3.080	3.398
A10R4	10337	37883	3.67	16468 *3321	43326 *7212	1.729 *2.631	1.715 *3.607
A15R4	26898	73956	3.71	35404 *4223	83290 *16337	1.653 *3.804	1.619 *3.447
A20R4	35011	105469	3.01	7947 *12383	19801 *33364	3.513 *3.276	3.386 *2.305
A25R	5582	30169	3.67	734	643	3.400	3.760
A35SR	9770	13784	1.41	2883	3285	3.704	3.728
A55R	14603	34340	1.66	3669	#2411	3.476	3.113
A5R	4159	7977	1.91	1183	1605	2.946	3.980
A5EE	87880	129470	1.47	3383	2931	3.539	3.411

Temperature susceptibility

$$= \frac{\text{LogLog viscosity @ } T_2 - \text{LogLog viscosity @ } T_1}{\text{Log } T_1 - \text{Log } T_2}$$

* : the meaning for the codes for the binders can be found in Table 4.2

Table B.4 Continued

	ABS VISCOSITY (POISE) @ 60 °C		HARDENING	KIN. VISCOSITY (CST) @ 135°C		TEMPERATURE SUSCEPTIBILITY (60°C TO 135°C)	
	ORI	TFOT	INDEX	ORI	TFOT	ORI	TFOT
B	2194	4228	1.93	453	686	3.407	3.628
B10C	3661	6080	1.66	540	1171	3.480	3.106
B5C	4757	9888	2.08	642	827	3.666	3.626
B5R8	3628	7607	2.10	716	1047	3.262	3.277
B15R4	14157	21922	1.56	*7066	*7767	*2.294	*2.360
B35SR	6688	8665	1.60	1215	1272	2.963	3.169
B3E	2712	4228	1.63	763	1126	3.098	2.691
B5E	2682	4757	2.14	572	1268	2.614	2.557
B8S	3953	8926	1.50	2302	3157	2.652	2.596
B35SM	67963	90957	1.34	2660	3493	3.380	3.304
C	546	1349	2.47	206	315	3.611	3.627
C5E	1403	2843	2.03	766	1028	2.847	2.919
C35SE	12993	16165	1.09	2357	2463	2.926	2.628

Temperature susceptibility

$$= \frac{\text{LogLog viscosity @ } T_2 - \text{LogLog viscosity @ } T_1}{\text{Log } T_1 - \text{Log } T_2}$$

Viscosity @ centipoise

T_1, T_2 = absolute temperature

* is based on Haake viscometer

Table B.5 Constant power viscosity of original asphalts with & without modifiers

Asphalt	Constant power viscosity (Pa s) 5°C (41°F) C Value		η_i	25°C (77°F) C Value		η_i
AC-30	0.88		4.3E08	1.22		1.65E05
	0.86		5.1E08	1.39		1.69E05
		avg	**4.7E08**		avg	**1.87E09**
+5%	0.77		2.2E09	1.10		7.75E05
Gilsonite	0.65		2.9E09	1.11		6.66E05
		avg	**2.8E09**		avg	**7.21E09**
+10%	1.13		1.3E09	0.99		4.75E06
Gilsonite	1.18		1.2E09	0.85		6.17E06
		avg	**1.3E09**		avg	**5.46E08**
+15%	0.90		1.6E09	0.82		9.95E06
Gilsonite	0.91		2.0E09	0.87		8.14E06
		avg	**1.21E08**		avg	**9.05E08**
+5%	0.88		2.5E08	1.01		3.72E05
Carbon B	0.94		1.8E08	1.09		3.09E05
		avg	**1.65E08**		avg	**3.41E05**
+10%	1.12		1.6E08	0.88		5.84E05
Carbon B	1.13		1.3E08	0.96		5.50E05
		avg	**1.46E08**		avg	**5.67E05**
+15%	0.70		3.9E08	1.02		3.83E05
Carbon B.	0.81		3.4E08	1.06		3.79E05
		avg	**3.66E08**		avg	**3.81E06**
	15°C (99°F)			25°C (77°F)		
AC-30	1.27		4.86E06	1.22		1.65E05
	1.22		5.04E06	1.39		1.69E05
		avg	**4.99E08**		avg	**1.87E09**
+5%	0.82		1.66E07	1.10		7.75E05
Gilsonite	0.82		1.81E07	1.11		6.66E05
		avg	**1.74E07**		avg	**7.21E06**
+10%	0.81		8.17E07	0.99		4.75E06
Gilsonite	0.82		8.06E07	0.85		6.17E06
		avg	**8.12E07**		avg	**9.46E06**
+5%	1.27		4.34E06	1.01		3.72E05
Carbon B	1.27		4.12E06	1.09		3.09E05
		avg	**4.23E06**		avg	**3.41E09**
+10%	1.55		2.19E06	0.88		5.84E05
Carbon B	1.55		1.87E06	0.96		5.50E05
		avg	**2.03E08**		avg	**5.67E09**
+15%	1.06		5.01E06	1.02		3.83E05
Carbon B.	1.09		5.57E06	1.06		3.79E05
		avg	**6.04E08**		avg	**3.81E06**

Table E.5 Continued

Asphalt	Constant Power Viscosity (Pa s) 5°C (41°F) C Value		η_j	25°C (77°F) C Value		η_j
AC-30						
+2%	0.92		1.6E08	0.91		5.75E05
GTR-80	0.91		1.7E08	1.05		4.58E05
		avg	**1.65E08**		avg	**5.17E05**
+5%	0.61		4.7E08	0.80		1.26E06
GTR-80	0.57		4.9E08	0.86		1.18E06
		avg	**4.8E08**		avg	**1.22E06**
+8%	0.76		2.6E08	0.77		1.76E06
GTR-80	0.79		3.1E08	0.89		1.46E06
		avg	**2.85E08**		avg	**1.61E06**
+10%	1.24		9.2E07	0.72		1.34E06
GTR-40	0.75		2.6E08	0.76		9.17E05
		avg	**1.76E08**		avg	**1.13E06**
+15%	0.65		1.6E08	0.49		8.96E06
GTR-40	0.51		1.9E08	0.37		1.14E07
		avg	**1.75E08**		avg	**1.02E07**
+20%	0.58		2.0E08	0.39		1.60E07
GTR-40	0.60		2.1E08	0.44		1.45E07
		avg	**2.05E08**		avg	**1.53E07**
+2%	0.66		2.6E08	0.93		3.74E05
SBR	0.91		2.1E08	0.97		3.49E05
		avg	**2.35E08**		avg	**3.62E05**
+3.5%	0.88		1.60E08	0.77		5.80E05
SBR	0.97		1.50E08	0.67		5.98E05
		avg	**1.55E08**		avg	**5.89E05**
+5%	0.89		3.10E08	1.24		3.40E05
SBR	1.16		1.40E08	1.44		2.00E05
		avg	**2.25E08**		avg	**2.70E05**
+5%	0.85		1.00E09	1.06		6.80E05
EVA	0.54		1.10E09	1.03		5.42E05
		avg	**1.05E09**		avg	**6.11E05**
+5%	0.39		2.00E09	0.82		7.69E06
SEBS	0.38		1.60E09	0.79		5.27E06
		avg	**1.80E09**		avg	**6.48E06**

Table B.5 Continued

Constant Power Viscosity (Pa s)

Asphalt	5°C (41°F)			25°C (77°F)		
	C Value		a_j	C Value		a_j
AC-20	0.78		2.40E08	0.79		8.88E05
	0.99		2.70E08	0.76		8.73E05
		avg	**2.55E08**		avg	**8.81E05**
+5%	0.85		2.50E08	0.82		1.54E06
Gilsonite	0.78		5.20E08	0.83		1.78E06
		avg	**3.85E08**		avg	**1.66E06**
+10%	0.61		2.50E08	1.04		2.57E05
Carbon B.	0.87		1.60E08	0.90		4.51E05
		avg	**2.35E08**		avg	**3.54E05**
+5%	0.47		5.50E08	0.85		7.11E05
GTR-80	0.50		6.00E08	0.91		6.26E05
		avg	**5.75E08**		avg	**6.68E05**
+15%	0.52		5.30E08	0.58		3.64E06
GTR-40	0.35		6.70E08	0.67		1.48E06
		avg	**6.00E08**		avg	**2.56E06**
+3.5%	0.43		3.60E08	0.82		7.92E05
SBR	0.38		4.80E08	0.72		9.45E05
		avg	**4.20E08**		avg	**8.69E05**
+3.5%	0.53		6.70E08	0.68		5.93E06
SEBS	0.58		7.30E08	0.61		7.46E06
		avg	**7.00E08**		avg	**6.70E06**
+3%	1.21		1.10E08	0.82		7.16E05
EVA	0.82		2.30E08	0.89		5.65E05
		avg	**1.70E08**		avg	**6.41E05**
+5%	1.04		5.10E08	0.74		1.46E06
EVA	0.81		4.30E08	0.78		1.58E06
		avg	**4.70E08**		avg	**1.52E06**
+8%	0.47		4.00E08	0.63		3.81E06
EVA	0.49		4.90E08	0.47		2.42E06
		avg	**4.45E08**		avg	**3.12E06**
AC-5	0.72		2.68E07	0.72		1.28E05
	0.56		5.28E07	0.70		1.44E05
		avg	**3.98E07**		avg	**1.36E05**
+5%	0.56		7.28E07	0.88		1.12E05
EVA	0.36		2.10E08	0.81		1.53E05
		avg	**1.42E08**		avg	**1.33E05**
+3.5	0.48		3.10E08	0.72		1.35E06
SEBS	0.40		3.40E08	0.77		9.24E05
		avg	**3.25E08**		avg	**1.14E06**

Table 8.6 TFOT Effects on Constant Power Viscosity

CONSTANT POWER VISCOSITY (Pa. S)				
	5°C (41°F)		25°C (77°F)	
	ORIGINAL	TFOT (325°F)	ORIGINAL	TFOT (325°F)
AC-30	4.70×10^9	5.40×10^8	1.67×10^5	5.95×10^5
+5% Gilsonite	2.60×10^9	4.30×10^9	7.21×10^5	3.00×10^9
10% Gilsonite	1.30×10^9	2.90×10^9	5.46×10^6	9.77×10^9
15% Gilsonite	1.21×10^9	4.70×10^9	9.05×10^4	1.00×10^7
5% Carbon B	1.65×10^9	4.85×10^9	3.41×10^5	6.65×10^5
10% Carbon B	1.45×10^9	1.10×10^9	5.67×10^5	1.41×10^8
15% Carbon B.	3.65×10^8	1.50×10^9	3.81×10^5	1.46×10^9
2% GTR-80	1.65×10^9	2.50×10^9	5.17×10^5	1.50×10^9
5% GTR-80	4.80×10^9	5.90×10^9	1.22×10^6	2.00×10^9
8% GTR-80	2.85×10^9	6.60×10^8	1.61×10^4	3.02×10^9
10% GTR-40	1.76×10^9	1.50×10^9	1.13×10^6	5.76×10^9
15% GTR-40	1.75×10^8	1.10×10^9	1.02×10^7	1.46×10^7
20% GTR-40	2.05×10^9	1.40×10^9	1.53×10^7	1.67×10^7
2% SBR	2.35×10^9	3.30×10^9	3.62×10^5	1.67×10^6
3.5% SBR	1.55×10^8	3.70×10^9	5.89×10^5	1.53×10^6
5% SBR	2.25×10^9	2.60×10^9	2.70×10^5	1.27×10^9
5% EVA	1.05×10^9	1.40×10^9	6.11×10^5	2.34×10^9
5% SEBS	1.80×10^9	2.30×10^9	6.48×10^4	9.71×10^9

Table B.8 Continued

CONSTANT POWER VISCOSITY (Pa. S))				
	5°C (41°F)		25°C (77°F)	
	ORIGINAL	TFOT (325°F)	ORIGINAL	TFOT (325°F)
AC-20	$2.55X10^{8}$	$5.20X10^{8}$	$8.81X10^{5}$	$1.26X10^{6}$
+5% Gilsonite	$3.85X10^{8}$	$5.80X10^{8}$	$1.66X10^{6}$	$7.45X10^{6}$
10% Carbon B	$2.05X10^{8}$	$3.70X10^{8}$	$3.54X10^{5}$	$2.13X10^{6}$
5% GTR-80	$5.75X10^{8}$	$7.10X10^{8}$	$6.69X10^{5}$	$1.72X10^{6}$
15% GTR-40	$8.00X10^{8}$	$1.60X10^{9}$	$2.58X10^{6}$	$1.04X10^{7}$
3.5% SBR	$4.20X10^{8}$	$4.90X10^{8}$	$8.69X10^{5}$	$2.09X10^{6}$
3% EVA	$1.70X10^{8}$	$2.70X10^{8}$	$8.41X10^{5}$	$9.97X10^{5}$
5% EVA	$4.70X10^{8}$	$5.20X10^{8}$	$1.52X10^{6}$	$1.55X10^{6}$
8% EVA	$4.45X10^{8}$	$8.40X10^{8}$	$3.12X10^{6}$	$4.27X10^{6}$
3.5% SEBS	$7.00x10^{8}$	$9.50x10^{8}$	$8.70x10^{6}$	$1.85x10^{7}$
AC-5	$3.98x10^{7}$	$8.53x10^{7}$	$1.35x10^{5}$	$4.76x10^{5}$
+5% EVA	$1.42x10^{8}$	$2.80x10^{8}$	$1.33x10^{5}$	$8.93x10^{5}$
3.5% SEBS	$3.25x10^{8}$	$5.80x10^{8}$	$1.14x10^{6}$	$5.86x10^{6}$

Table 6.7 TFOT Effects on Penetration

	PENETRATION @ 25° C (100 g, 5 sec)			PENETRATION@ 4°C (200 g, 60 sec)		PENETRATION RATIO	
	ORI	TFOT	RETENTION(%)	ORI	TFOT	ORI	TFOT
AC-30	59	41	69.5	20	13	2.95	3.15
A5O	48	25	52.1	13	10	3.69	2.50
A10O	28	19	67.9	11	6	2.55	3.17
A15O	20	14	70.0	6	3	3.33	4.67
A5C	63	35	55.6	18	12	3.50	2.92
A10C	60	34	56.7	17	12	3.53	2.83
A15C	50	34	68.0	16	13	3.13	2.62
A2R8	54	39	72.2	18	15	3.00	2.60
A5R8	52	40	76.9	19	16	2.74	2.50
A6R8	46	35	76.1	21	15	2.19	2.33
A10S4	45	27	60.0	15	9	3.00	3.00
A15R6	39	26	66.7	19	11	2.05	2.36
A20S4	29	26	89.7	13	11	2.23	2.36
A25R	52	35	67.3	17	13	3.06	2.69
A35S8	50	35	70.0	17	15	2.94	2.33
A55R	47	32	68.1	19	15	2.47	2.13
A5E	46	35	76.1	17	16	2.71	2.19
A5SE	33	24	72.7	14	13	2.36	1.85

* :the meaning for the codes for the binders can be found in Table 4.2

Table B.7 Continued

	PENETRATION @ 25° C (100 g, 5 sec)			PENETRATION @ 4°C (200 g, 60 sec)		PENETRATION RATIO	
	ORI	TFOT	RETENTION(%)	ORI	TFOT	ORI	TFOT
B	60	44	73.3	17	14	3.53	3.14
B10C	55	43	78.2	17	13	3.24	3.31
B5E	38	30	78.9	12	10	3.17	3.00
B5R8	52	36	69.2	18	14	2.88	2.57
B15R4	44	30	68.2	16	14	2.75	2.14
B35SR	53	38	71.7	17	13	3.12	2.92
B3R	59	41	69.5	17	15	3.47	2.73
B5R	63	32	50.8	22	19	2.86	1.68
B6R	44	37	84.1	21	17	2.10	2.18
B35RE	42	31	73.8	20	18	2.10	1.72
C	127	76	59.8	42	30	3.02	2.53
C5R	76	48	63.2	38	24	2.00	2.00
C35SR	60	41	68.3	27	22	2.22	1.86

Table B.8 Results of Infrared Spectroscopy Test on Unaged and Aged Modified Asphalts

Asphalt		Original		TFOT (163°C)
AC-30		0.36855		0.41369
		0.36418		0.41319
	avg	0.36637	avg	0.41344
+5%		0.38379		0.41756
Gilsonite		0.38645		0.41706
	avg	0.38512	avg	0.41731
+10%		0.38751		0.43878
Gilsonite		0.38547		0.43095
	avg	0.38649	avg	0.43487
+15%		0.38984		0.43906
Gilsonite		0.38746		0.44430
	avg	0.38865	avg	0.44168
+2%		0.31295		0.43090
GTR-80		0.31466		0.38958
	avg	0.31381	avg	0.41024
+5%		0.30564		0.38958
GTR-80		0.30618		0.38563
	avg	0.30591	avg	0.38761
+8%		0.33473		0.40523
GTR-80		0.33280		0.41326
	avg	0.33377	avg	0.40925
+10%		0.35227		0.43876
GTR-40		0.35772		0.43980
	avg	0.35503	avg	0.43928
+15%		0.37958		0.40496
GTR-40		0.37847		0.41860
	avg	0.37903	avg	0.41178
+20%		0.33031		0.40573
GTR-40		0.33603		0.39673
	avg	0.33317	avg	0.40123
+2%		0.39740		0.41958
SBR		0.40776		0.41626
	avg	0.40258	avg	0.41792
+3.5%		0.40873		0.41177
SBR		0.40412		0.42454
	avg	0.40643	avg	0.41816
+5%		0.37892		0.40095
SBR		0.38534		0.38834
	avg	0.38213	avg	0.39466
+5%		0.46378		0.51317
EVA		0.46071		0.52082
	avg	0.46225	avg	0.51700

Table B.8 Continued

Asphalt		Original		TFOT (163°C)
AC-20		0.27098		0.33398
		0.25782		0.31607
	avg	**0.26440**	avg	**0.32503**
+5%		0.28819		0.33693
Gilsonite		0.28273		0.33055
	avg	**0.28546**	avg	**0.33374**
+5%		0.34966		0.40441
GTR-80		0.35012		0.40494
	avg	**0.34989**	avg	**0.40468**
+15%		0.34585		0.43358
GTR-40		0.34438		0.43980
	avg	**0.34512**	avg	**0.43669**
+3.5%		0.34438		0.46266
SBR		0.35010		0.47034
	avg	**0.34724**	avg	**0.46650**
+3%		0.34985		0.37913
EVA		0.35118		0.37890
	avg	**0.35052**	avg	**0.37902**
+5%		0.40955		0.45164
EVA		0.40061		0.45589
	avg	**0.40508**	avg	**0.45377**
+8%		0.39918		0.44978
EVA		0.40445		0.44749
	avg	**0.40182**	avg	**0.44864**

APPENDIX C

RESULTS OF CONSISTENCY AND RHEOLOGY TESTS AFTER TFOT AND RTFOT AGING PROCESS

Table C-1 TFOT & RTFOT Effects on the absolute viscosity at 60°C (140°F)

Asphalt	Original		Oven Temperature 141°C Absolute Viscosity (Poise)	183°C	185°C
AC-30	3034	TFOT	3919	6202	10876
		RTFOT	8491	8351	19939
AC-30+ 5% Gilsonite	6322	TFOT	9484	18008	28148
		RTFOT	12985	19765	44002
AC-30+ 10% Carbon Black	3295	TFOT	5828	10685	14269
		RTFOT	8104	11829	23541
			183°C	**185°C**	**198°C**
AC-30+ 5% GTR-80	8427	TFOT	12081	30889	73701
		RTFOT	24598	39492	78894
AC-30+ 15% GTR-340	26890	TFOT	72956	176384	425648
		RTFOT	-	-	-
AC-30+ 3.5% SBR	9770	TFOT	13784	32644	105117
		RTFOT	40410	56283	105452
AC-30+ 5% EVA	4159	TFOT	7977	9218	13756
		RTFOT	8989	24080	50752
AC-30+ 5% SEBS	87880	TFOT	93852	115937	243290
		RTFOT	96135	178817	445938
AC-20+ 5% EVA	2882	TFOT	4757	10397	20205
		RTFOT	8347	21887	40687
AC-5+ 5% EVA	1403	TFOT	2843	5881	18097
		RTFOT	4042	19578	25561
AC-20+ 3.5% SEBS	87963	TFOT	90987	118204	178338
		RTFOT	92965	129856	234572
AC-5+ 3.5% SEBS	12993	TFOT	14145	27385	130150
		RTFOT	87279	171209	200393

Table C-2. TFOT & RTFOT Effects on the penetration at 4°C (39.2°F)

Asphalt	Original		Oven Temperature 141°C	163°C Penetration @ 4°C	185°C
AC-30	20	TFOT	15	13	12
		RTFOT	18	18	14
AC-30+ 5% Gilsonite	13	TFOT	12	10	10
		RTFOT	11	10	8
AC-30+ 10% Carbon Black	17	TFOT	18	12	12
		RTFOT	15	12	11
			163°C	**185°C**	**196°C**
AC-30+ 5% GTR-80	19	TFOT	18	18	14
		RTFOT	15	13	12
AC-30+ 15% GTR-40	19	TFOT	11	10	10
		RTFOT	-	-	-
AC-30+ 3.5% SBR	17	TFOT	16	15	14
		RTFOT	14	13	12
AC-30+ 5% EVA	17	TFOT	16	12	11
		RTFOT	14	12	10
AC-30+ 5% SEBS	14	TFOT	11	10	7
		RTFOT	11	9	8
AC-20+ 5% EVA	22	TFOT	19	18	12
		RTFOT	20	17	13
AC-5+ 5% EVA	38	TFOT	25	23	22
		RTFOT	27	25	20
AC-20+ 3.5% SEBS	20	TFOT	18	15	15
		RTFOT	13	9	8
AC-5+ 3.5% SEBS	27	TFOT	22	19	18
		RTFOT	20	18	17

Table C-3. TFOT & RTFOT Effects on the penetration at 25°C (77°F)

Asphalt	Original		Oven Temperature 141°C	 163°C Penetration @ 25°C	 185°C
AC-30	59	TFOT RTFOT	46 42	41 38	30 27
AC-30+ 5% Gilsonite	48	TFOT RTFOT	30 26	25 22	19 17
AC-30+ 10% Carbon Black	60	TFOT RTFOT	46 36	34 30	27 22
			163°C	185°C	196°C
AC-30+ 5% GTR-80	52	TFOT RTFOT	40 31	32 25	27 23
AC-30+ 15% GTR-40	39	TFOT RTFOT	26 -	21 -	17 -
AC-30+ 3.5% SBR	50	TFOT RTFOT	35 29	33 25	25 22
AC-30+ 5% EVA	46	TFOT RTFOT	35 27	25 22	24 19
AC-30+ 5% SEBS	33	TFOT RTFOT	24 20	18 17	15 15
AC-20+ 5% EVA	63	TFOT RTFOT	32 32	28 27	22 22
AC-5+ 5% EVA	76	TFOT RTFOT	48 49	43 42	33 33
AC-20+ 3.5% SEBS	42	TFOT RTFOT	31 20	30 17	28 15
AC-5+ 3.5% SEBS	62	TFOT RTFOT	41 35	36 30	30 28

Table C-4. TFOT & RTFOT Effects on the percent penetration retained at 4°C (39.2°F)

		Oven Temperature		
		141°C	163°C	165°C
Asphalt		Penetration Retation (%)		
AC-30	TFOT	76.0	65.0	60.0
	RTFOT	90.0	80.0	70.0
AC-30+ 5% Gilsonite	TFOT	92.3	76.9	76.9
	RTFOT	84.6	76.9	61.5
AC-30+ 10% Carbon Blac	TFOT	94.1	70.6	70.6
	RTFOT	88.2	70.6	64.7
		163°C	185°C	196°C
AC-30+ 5% GTR-80	TFOT	84.2	84.2	73.7
	RTFOT	78.9	66.4	63.2
AC-30+ 15% GTR-40	TFOT	57.9	52.6	52.6
	RTFOT	-	-	-
AC-30+ 3.5% SBR	TFOT	94.1	88.2	62.4
	RTFOT	62.4	76.5	70.6
AC-30+ 5% EVA	TFOT	94.1	70.6	64.7
	RTFOT	82.4	70.6	58.8
AC-30+ 5% SEBS	TFOT	78.6	71.4	50.0
	RTFOT	76.6	64.3	57.1
AC-20+ 5% EVA	TFOT	86.4	61.8	54.5
	RTFOT	90.9	77.3	59.1
AC-5+ 5% EVA	TFOT	65.8	60.5	57.9
	RTFOT	71.1	65.6	52.6
AC-20+ 3.5% SEBS	TFOT	90.0	75.0	75.0
	RTFOT	65.0	45.0	40.0
AC-5+ 3.5% SEBS	TFOT	61.5	70.4	66.7
	RTFOT	74.1	66.7	63.0

Table C-5. TFOT & RTFOT Effects on the percent penetration retained at 25°C (77°F)

Asphalt		Oven Temperature 141°C	 163°C	 185°C
		Penetration Retation (%)		
AC-30	TFOT	78.0	69.5	50.8
	RTFOT	71.2	64.4	45.8
AC-30+ 5% Gilsonite	TFOT	62.5	52.1	39.6
	RTFOT	54.2	45.8	35.4
AC-30+ 10% Carbon Blac	TFOT	76.7	56.7	45.0
	RTFOT	60.0	50.0	36.7
		163°C	**185°C**	**196°C**
AC-30+ 5% GTR-80	TFOT	76.9	61.5	51.9
	RTFOT	59.6	48.1	44.2
AC-30+ 15% GTR-40	TFOT	66.7	53.8	43.5
	RTFOT	-	-	-
AC-30+ 3.5% SBR	TFOT	70.0	66.0	50.0
	RTFOT	58.0	50.0	44.0
AC-30+ 5% EVA	TFOT	76.1	54.3	52.2
	RTFOT	58.7	47.8	41.3
AC-30+ 5% SEBS	TFOT	72.7	54.5	45.5
	RTFOT	60.6	51.5	45.5
AC-20+ 5% EVA	TFOT	50.8	44.4	34.9
	RTFOT	50.8	42.9	34.9
AC-5+ 5% EVA	TFOT	63.2	55.6	43.4
	RTFOT	64.5	55.3	43.4
AC-20+ 3.5% SEBS	TFOT	73.8	71.4	66.7
	RTFOT	47.6	40.5	35.7
AC-5+ 3.5% SEBS	TFOT	66.1	58.1	48.4
	RTFOT	56.5	48.4	45.2

Table C-6.TFOT & RTFOT Effects on the schweyer constant power viscosity at temperature of 5°C (41°F)

Asphalt	Original		Oven Temperature 141°C Constant Power Viscosity(Pa s)	163°C	185°C
AC-30	$4.70x10^8$	TFOT RTFOT	$4.80x10^8$ $5.70X10^8$	$5.40x10^8$ $6.00X10^8$	$7.50x10^8$ $1.00X10^9$
AC-30+ 5% Gilsonite	$2.60x10^9$	TFOT RTFOT	$3.70x10^9$ $1.40X10^9$	$4.30x10^9$ $3.60X10^9$	$5.00x10^9$ $4.60X10^9$
AC-30+ 10% Carbon Black	$1.45x10^8$	TFOT RTFOT	$1.10x10^9$ $5.00X10^8$	$1.90x10^9$ $7.40X10^8$	$2.20x10^9$ $3.00X10^9$
			163°C	185°C	196°C
AC-30+ 5% GTR-80	$4.80x10^8$	TFOT RTFOT	$6.90x10^8$ $7.40X10^8$	$9.00x10^8$ $1.30X10^9$	$1.10x10^9$ $1.30x10^9$
AC-30+ 3.5% SBR	$1.55x10^8$	TFOT RTFOT	$3.70x10^8$ $1.60X10^8$	$9.10x10^8$ $6.00X10^8$	$1.70x10^9$ $1.60x10^9$
AC-30+ 5% EVA	$1.05x10^9$	TFOT RTFOT	$1.40x10^9$ $1.60x10^9$	$2.10x10^9$ $2.50x10^9$	$2.90x10^9$ $4.00x10^9$
AC-30+ 5% SEBS	$1.80x10^9$	TFOT RTFOT	$2.30x10^9$ $3.00x10^9$	$2.40x10^9$ $3.60x10^9$	$3.10x10^9$ $4.60x10^9$
AC-20+ 5% EVA	$4.70x10^8$	TFOT RTFOT	$5.20x10^8$ $7.90x10^8$	$7.90x10^8$ $1.40x10^9$	$9.40x10^8$ $1.60x10^9$
AC-5+ 5% EVA	$1.42x10^8$	TFOT RTFOT	$2.60x10^8$ $1.30x10^8$	$3.50x10^8$ $1.60x10^8$	$3.60x10^8$ $1.70x10^8$
AC-20+ 3.5% SEBS	$7.00x10^8$	TFOT RTFOT	$9.50x10^8$ $1.20x10^9$	$2.60x10^9$ $2.90x10^9$	$3.80x10^9$ $5.20x10^9$
AC-5+ 3.5% SEBS	$3.25x10^8$	TFOT RTFOT	$5.80x10^8$ $5.90x10^8$	$6.00x10^8$ $6.10x10^8$	$7.30x10^8$ $7.90x10^8$

Note:RTFOT can not be performed on coarse rubber modified binders, because the materials will come out during testing

Table C-7 TFOT & RTFOT Effects on the schweyer constant power viscosity at temperature of 25°C (77°F)

Asphalt	Original		Oven Temperature 141°C	 163°C	 185°C
			Constant Power Viscosity (Pa s)		
AC-30	$1.67x10^5$	TFOT	$3.80x10^5$	$5.95x10^5$	$1.86x10^6$
		RTFOT	$7.20X10^5$	$8.77X10^5$	$2.22X10^6$
AC-30+ 5% Gilsonite	$7.21x10^5$	TFOT	$1.25x10^5$	$1.00x10^5$	$4.49x10^6$
		RTFOT	$3.26X10^5$	$4.68X10^5$	$6.28X10^5$
AC-30+ 10% Carbon Black	$5.67x10^5$	TFOT	$7.50x10^5$	$1.41x10^6$	$2.67x10^5$
		RTFOT	$1.10X10^6$	$1.52X10^5$	$4.51X10^5$
			163°C	185°C	196°C
AC-30+ 5% GTR-80	$1.22x10^6$	TFOT	$2.00x10^6$	$2.00x10^6$	$8.04x10^6$
		RTFOT	$2.70X10^6$	$4.83X10^6$	$1.05X10^7$
AC-30+ 3.5% SBR	$5.89x10^5$	TFOT	$1.53x10^6$	$1.84x10^6$	$6.49x10^6$
		RTFOT	$1.68X10^6$	$2.16X10^6$	$7.02x10^6$
AC-30+ 5% EVA	$6.11x10^6$	TFOT	$2.34x10^6$	$2.64x10^6$	$4.82x10^6$
		RTFOT	$3.33x10^6$	$7.85x10^6$	$1.15x10^7$
AC-30+ 5% SEBS	$6.48x10^6$	TFOT	$9.71x10^6$	$2.06x10^7$	$2.77x10^7$
		RTFOT	$4.01x10^7$	$4.79x10^7$	$6.76x10^7$
AC-20+ 5% EVA	$1.52x10^6$	TFOT	$1.55x10^6$	$2.68x10^6$	$3.56x10^6$
		RTFOT	$2.17x10^6$	$3.21x10^6$	$8.65x10^6$
AC-5+ 5% EVA	$1.33x10^5$	TFOT	$6.93x10^5$	$8.50x10^5$	$1.59x10^6$
		RTFOT	$9.06x10^5$	$2.24x10^6$	$3.20x10^6$
AC-20+ 3.5% SEBS	$6.70x10^6$	TFOT	$1.85x10^7$	$2.71x10^7$	$3.20x10^7$
		RTFOT	$2.13x10^7$	$4.20x10^7$	$6.81x10^7$
AC-5+ 3.5% SEBS	$1.14x10^6$	TFOT	$5.86x10^6$	$8.91x10^5$	$1.09x10^7$
		RTFOT	$7.05x10^6$	$9.81x10^6$	$1.10x10^7$

Note=RTFOT can not be performed on coarse rubber modified binders, because the materials will come out during testing

Table C-8. TFOT & RTFOT Effects on the carbonyl ratio as determined by Infrared Spectroscopy test

Asphalt	Original		Oven Temperature 141°C	 163°C	 185°C
			Carbonyl Ratio		
AC-30	0.36637	TFOT	0.38061	0.41344	0.48551
		RTFOT	0.44714	0.45427	0.61725
AC-30+ 5% Gilsonite	0.38512	TFOT	0.39702	0.41731	0.45094
		RTFOT	0.46103	0.46913	0.48259

			163°C	185°C	198°C
AC-30+ 5% GTR-80	0.30591	TFOT	0.38761	0.43054	0.49647
		RTFOT	0.42271	0.45433	0.48690
AC-30+ 15% GTR-40	0.37903	TFOT	0.41178	0.42208	0.46413
		RTFOT	-	-	-
AC-30+ 3.5% SBR	0.40843	TFOT	0.41818	0.43420	0.47715
		RTFOT	0.46008	0.48429	0.51844
AC-30+ 5% EVA	0.41389	TFOT	0.44131	0.48477	0.51244
		RTFOT	0.49569	0.53952	0.56406
AC-30+ 5% SEBS	0.28387	TFOT	0.32543	0.40040	0.49284
		RTFOT	0.42628	0.45589	0.54901
AC-20+ 5% EVA	0.40508	TFOT	0.45377	0.48827	0.53840
		RTFOT	0.46369	0.53126	0.54383
AC-5+ 5% EVA	0.35312	TFOT	0.37291	0.45779	0.47164
		RTFOT	0.49480	0.52452	0.51943
AC-20+ 3.5% SEBS	0.28306	TFOT	0.33187	0.38572	0.38558
		RTFOT	0.40084	0.44680	0.46974
AC-5+ 3.5% SEBS	0.29791	TFOT	0.30502	0.37461	0.40494
		RTFOT	0.38258	0.41498	0.42828

Table C-9. TFOT & RTFOT Effects on the Carbonyl Ratio Index.

Asphalt	Original		Oven Temperature 141°C Carbonyl Ratio Index	 163°C	 185°C
AC-30	0.36637	TFOT	1.039	1.128	1.325
		RTFOT	1.220	1.240	1.685
AC-30+ 5% Gilsonite	0.38512	TFOT	1.031	1.084	1.171
		RTFOT	1.197	1.218	1.253
			163°C	185°C	196°C
AC-30+ 5% GTR-80	0.30591	TFOT	1.267	1.407	1.623
		RTFOT	1.382	1.485	1.592
AC-30+ 15% GTR-40	0.37503	TFOT	1.086	1.114	1.225
		RTFOT	-	-	-
AC-30+ 3.5% SBR	0.40643	TFOT	1.029	1.068	1.174
		RTFOT	1.132	1.192	1.276
AC-30+ 5% EVA	0.41389	TFOT	1.066	1.123	1.238
		RTFOT	1.198	1.304	1.363
AC-30+ 5% SEBS	0.28387	TFOT	1.146	1.411	1.736
		RTFOT	1.502	1.606	1.934
AC-20+ 5% EVA	0.40508	TFOT	1.120	1.205	1.324
		RTFOT	1.145	1.311	1.343
AC-5+ 5% EVA	0.35312	TFOT	1.056	1.296	1.336
		RTFOT	1.401	1.485	1.471
AC-20+ 3.5% SEBS	0.26306	TFOT	1.172	1.292	1.362
		RTFOT	1.416	1.578	1.660
AC-5+ 3.5% SEBS	0.29791	TFOT	1.024	1.257	1.359
		RTFOT	1.284	1.393	1.431

APPENDIX D

RESULTS OF MIXTURE STRENGTH TESTS

Table D-1 Results of resilient modulus tests on dense-graded mixtures

Unmodified AC-30 Asphalt @ 5°C (41°F)

					No aging		PD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.515	2.533	2.554	2.537	2.541	2.544
Resilient Modulus	Instantaneous	Cycle Frequency	0.33 Hz	0°	17.527	18.476	19.813	21.674	17.877	15.644
				90°	17.181	17.136	17.043	22.555	15.899	16.046
			0.50 Hz	0°	17.329	18.122	19.586	22.323	17.776	14.558
				90°	17.257	16.564	15.581	22.275	15.931	15.789
			1 Hz	0°	17.789	17.811	19.315	22.416	17.642	16.028
				90°	16.933	16.883	18.559	21.770	16.935	15.785
			Average		17.353	17.499	18.483	22.186	17.010	15.648
	Total		0.33 Hz	0°	13.642	13.903	15.868	18.321	13.238	11.742
				90°	12.701	13.462	12.771	18.422	12.685	11.279
			0.50 Hz	0°	13.592	14.285	15.190	18.737	13.436	11.186
				90°	12.775	13.386	12.814	18.817	12.474	11.520
			1 Hz	0°	13.836	14.422	16.420	18.731	13.551	11.917
				90°	12.727	13.578	14.237	18.741	12.915	11.593
			Average		13.212	13.841	14.717	18.628	13.068	11.540

Unit $\times 10^3$ psi

Results of ANOVA

```
Source       DF     Anova SS          Mean Square    F Value      Pr > F

ASPHALT      5      1.75998E+12       3.51995E+11      98.05      0.0001
CYCLE        2      1.01607E+10       5.08036E+09       1.42      0.2603
DEGREE       1      7.32514E+10       7.32514E+10      20.41      0.0001

R-Square = 0.950

Duncan       Mean        N   CYCLE       Duncan        Mean        N   Degree
Grouping                     Frequency   Grouping
A            1439825    12   1           A             1461872    18   0
A
A            1410183    12   0.5         B             1371656    18   90
A
A            1408283    12   0.33

      Note: Means with the same letter are not significantly different.
            (Alpha= 0.05)
```

Table 8-1 -- Continued

Unmodified AC-30 @ 25°C (77°F)

					No aging		F3 oven 98 days		Roof 6 months	
			Spec #		03	04	07	08	11	13
			Height (in.)		2.536	3.535	3.538	2.543	3.550	2.854
Resilient Modulus	Instantaneous	Cycle Frequency	0.33 Hz	0°	11.639	10.934	15.392	14.407	10.432	10.189
				90°	11.083	10.264	15.770	13.962	11.006	9.883
			0.50 Hz	0°	11.269	10.466	15.697	14.117	10.334	9.743
				90°	10.533	10.145	15.743	13.691	10.797	9.508
			1 Hz	0°	10.887	9.931	15.181	14.351	9.572	9.663
				90°	10.064	9.743	15.368	13.293	10.368	9.100
			Average		10.924	10.214	15.525	13.969	10.468	9.674
	Total		0.33 Hz	0°	5.548	5.331	10.617	9.460	4.836	4.658
				90°	6.118	4.905	10.616	9.345	5.068	4.368
			0.50 Hz	0°	5.963	5.385	10.599	9.458	4.971	4.739
				90°	5.110	4.896	10.563	9.346	5.111	4.491
			1 Hz	0°	5.466	5.323	10.600	9.592	5.062	4.886
				90°	5.149	4.884	10.436	9.458	5.199	4.565
			Average		5.358	5.121	10.559	9.443	5.040	4.617

Unit : x10³ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	3.03807E+12	4.05614E+11	2110.48	0.0001
CYCLE	2	5.73787E+08	3.86394E+08	1.49	0.2433
DEGREE	1	3.10249E+09	3.10249E+09	16.14	0.0004

R-Square = 0.997

Duncan Grouping	Mean	N	CYCLE Frequency
A	674325	12	1
A			
A	667753	12	0.5
A			
A	664767	12	0.33

Duncan Grouping	Mean	N	Degree
A	678344	18	0
B	659678	18	90

Note: Means with the same letter are not significantly different.
(Alpha= 0.05)

Table 0-1 -- Continued

Gilsonite modified AC-30 @ 5°C (41°F)

					No aging		FD oven 50 Days		Roof 6 months	
			Spec #		01	02	05	D6	05	10
			Height (in.)		2.518	2.526	2.541	2.821	2.527	2.543
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	21.108	21.563	23.208	22.692	20.562	19.512
				90°	21.164	20.501	20.916	20.687	20.596	19.062
			0.50 Hz	0°	20.642	22.074	22.822	22.888	21.166	22.345
				90°	20.864	20.982	21.460	20.400	21.256	20.402
			1 Hz	0°	20.444	21.818	22.601	22.259	20.772	19.246
				90°	20.813	21.462	21.535	20.716	20.638	20.085
			Average		20.839	21.400	22.050	21.586	20.815	20.185
	Total		0.33 Hz	0°	16.159	17.127	18.101	19.281	16.030	15.338
				90°	16.096	16.402	18.159	16.481	16.318	14.866
			0.50 Hz	0°	16.420	17.154	19.273	19.569	16.526	16.383
				90°	16.466	17.012	17.974	16.407	16.727	16.471
			1 Hz	0°	16.577	17.140	19.408	19.544	16.563	15.351
				90°	16.597	17.532	18.365	16.782	15.239	15.119
			Average		16.393	17.076	18.719	18.011	16.402	15.755

Unit: x10^5 psi

Results of ANOVA

```
Source     DF    Anova SS         Mean Square     F Value     Pr > F

ASPHALT    5     3.74470E+11      7.48941E+10       15.82     0.0001
CYCLE      2     1.26119E+10      6.30593E+09        1.33     0.2907
DEGREE     1     3.89997E+10      3.89997E+10        8.24     0.0079

Duncan      Mean      N    Degree
Grouping
A           1738839   18   0

B           1673011   18   90
```

Note: Means with the same letter are not significantly Different. (Alpha= 0.05)

Table 8-1 -- Continued

Gilsonite modified AC-30 @ 25°C (77°F)

<table>
<tr><td colspan="5"></td><td colspan="2">No aging</td><td colspan="2">FD oven 90 Days</td><td colspan="2">Roof 6 months</td></tr>
<tr><td colspan="3"></td><td colspan="2">Spec #</td><td>03</td><td>04</td><td>07</td><td>08</td><td>11</td><td>12</td></tr>
<tr><td colspan="3"></td><td colspan="2">Height (in.)</td><td>2.521</td><td>2.552</td><td>2.539</td><td>2.541</td><td>2.556</td><td>2.539</td></tr>
<tr><td rowspan="14">Resilient Modulus</td><td rowspan="7">Instantaneous</td><td rowspan="14">Cycle frequency</td><td rowspan="2">0.33 Hz</td><td>0°</td><td>12.518</td><td>11.934</td><td>16.277</td><td>16.417</td><td>13.414</td><td>13.417</td></tr>
<tr><td>90°</td><td>12.510</td><td>12.545</td><td>17.069</td><td>17.372</td><td>13.025</td><td>13.889</td></tr>
<tr><td rowspan="2">0.50 Hz</td><td>0°</td><td>12.214</td><td>11.966</td><td>16.503</td><td>16.526</td><td>12.264</td><td>13.102</td></tr>
<tr><td>90°</td><td>12.442</td><td>12.021</td><td>16.537</td><td>16.928</td><td>12.853</td><td>14.302</td></tr>
<tr><td rowspan="2">1 Hz</td><td>0°</td><td>12.192</td><td>11.723</td><td>15.720</td><td>16.700</td><td>12.809</td><td>12.867</td></tr>
<tr><td>90°</td><td>12.048</td><td>11.606</td><td>16.883</td><td>16.922</td><td>12.475</td><td>13.027</td></tr>
<tr><td colspan="2"><i>Average</i></td><td><i>12.321</i></td><td><i>11.976</i></td><td><i>16.498</i></td><td><i>16.921</i></td><td><i>12.973</i></td><td><i>13.434</i></td></tr>
<tr><td rowspan="7">Total</td><td rowspan="2">0.33 Hz</td><td>0°</td><td>7.112</td><td>6.747</td><td>11.676</td><td>11.812</td><td>8.107</td><td>8.059</td></tr>
<tr><td>90°</td><td>7.033</td><td>6.867</td><td>12.007</td><td>12.617</td><td>7.626</td><td>8.193</td></tr>
<tr><td rowspan="2">0.50 Hz</td><td>0°</td><td>7.207</td><td>6.798</td><td>11.658</td><td>12.187</td><td>7.994</td><td>8.269</td></tr>
<tr><td>90°</td><td>6.894</td><td>6.774</td><td>12.362</td><td>12.681</td><td>7.639</td><td>8.645</td></tr>
<tr><td rowspan="2">1 Hz</td><td>0°</td><td>7.338</td><td>6.937</td><td>11.502</td><td>11.938</td><td>7.965</td><td>8.217</td></tr>
<tr><td>90°</td><td>7.096</td><td>6.766</td><td>12.211</td><td>12.759</td><td>7.758</td><td>8.595</td></tr>
<tr><td colspan="2"><i>Average</i></td><td><i>7.130</i></td><td><i>6.615</i></td><td><i>11.903</i></td><td><i>12.366</i></td><td><i>7.846</i></td><td><i>8.352</i></td></tr>
</table>

Unit: x10^3 psi

Results of ANOVA

```
Source    DF   Anova SS        Mean Square    F Value    Pr > F

ASPHALT   5    1.77611E+12     3.55222E+11    602.30     0.0001
CYCLE     2    9.82889E+08     4.91444E+08      0.83     0.4455
DEGREE    1    2.32806E+09     2.32806E+09      3.95     0.0572

R-Square = 0.997

Duncan    Mean      N   CYCLE
Grouping                Frequency
A         910368   12   1
A
A         910142   12   0.5
A
A         899142   12   0.33
```

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table B-1 -- Continued

Carbon black modified AC-30 @ 5°C (41°F)

					No aging		FO oven 90 Days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.533	2.531	2.542	2.520	2.517	2.530
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	19.629	20.171	20.416	19.793	20.599	16.394
				90°	17.387	20.442	21.027	19.591	20.806	16.742
			0.50 Hz	0°	19.502	20.048	20.660	20.447	21.717	18.358
				90°	18.085	20.259	20.717	18.645	21.245	19.461
			1 Hz	0°	18.918	20.001	20.483	20.643	21.842	18.266
				90°	19.085	19.945	20.608	18.729	20.724	19.318
			Average		*18.884*	*20.144*	*20.652*	*19.641*	*21.222*	*18.090*
	Total		0.33 Hz	0°	14.146	15.865	16.519	16.073	16.745	12.471
				90°	15.768	15.896	17.847	15.826	16.370	14.993
			0.50 Hz	0°	15.496	15.904	17.167	16.437	17.205	14.150
				90°	15.512	15.953	17.541	15.144	16.298	14.722
			1 Hz	0°	15.535	16.872	17.218	15.532	17.374	14.410
				90°	15.802	16.153	17.324	15.347	16.229	14.729
			Average		*15.377*	*15.974*	*17.269*	*15.727*	*16.704*	*14.246*

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	3.33884E+11	6.67769E+10	20.70	0.0001
CYCLE	2	5.38249E+09	2.69124E+09	0.83	0.4451
DEGREE	1	2.73006E+09	2.73006E+09	0.85	0.3658

Table 8.1 -- Continued

Carbon black modified AC-30 @ 25°C (77°F)

					No aging		FD oven 90 days		Roof 9 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.535	2.650	2.537	2.939	2.559	2.540
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	12.598	12.427	19.435	15.990	11.911	12.089
				90°	12.487	12.254	14.959	16.072	12.427	12.948
			0.50 Hz	0°	12.211	12.184	14.701	15.532	11.684	11.652
				90°	12.457	12.200	14.413	15.762	12.092	12.287
			1 Hz	0°	11.963	12.123	14.379	15.398	11.199	11.589
				90°	12.225	11.820	14.232	15.692	11.918	12.235
			Average		*12.324*	*12.168*	*14.520*	*15.736*	*11.972*	*12.119*
	Total		0.33 Hz	0°	6.922	6.794	9.724	10.631	6.350	6.442
				90°	7.096	6.282	9.523	10.877	6.874	6.980
			0.50 Hz	0°	6.999	6.786	9.613	10.742	6.489	6.526
				90°	7.096	6.343	9.464	11.138	6.909	7.039
			1 Hz	0°	7.002	6.867	9.629	10.791	6.539	6.894
				90°	7.071	6.473	9.519	11.199	6.997	7.077
			Average		*7.993*	*6.591*	*9.577*	*10.996*	*6.693*	*9.793*

Unit: x10^5 psi

Results of ANOVA

```
Source       DF      Anova SS         Mean Square      F Value       Pr > F

ASPHALT      5       1.01731E+12      2.03462E+11      482.74        0.0001
CYCLE        2       7.87377E+08      3.93689E+08        0.93        0.4053
DEGREE       1       1.61872E+09      1.61872E+09        3.84        0.0604

R-Square = 0.989


Duncan       Mean      N   CYCLE
Grouping                   Frequency
A            798792    12  1
A
A            792267    12  0.5
A
A            787375    12  0.33
```

Note: Means with the same letter are not significantly different.
(Alpha= 0.05)

Table B.1 -- Continued

GTR-80 modified AC-30 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.548	2.540	2.593	2.582	2.612	2.576
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	17.299	18.878	19.256	19.852	13.763	16.311
				90°	17.550	16.882	19.732	17.734	13.332	16.256
			0.50 Hz	0°	17.239	17.004	19.960	19.721	13.976	16.638
				90°	17.661	16.694	19.932	17.568	13.450	15.582
			1 Hz	0°	17.368	16.770	19.540	18.524	16.506	16.393
				90°	17.730	16.562	20.018	17.925	13.307	16.113
			Average		17.475	17.132	15.740	18.554	14.722	16.049
	Total		0.33 Hz	0°	13.885	14.562	16.118	16.525	11.288	11.827
				90°	13.723	12.874	16.176	14.737	9.954	11.804
			0.50 Hz	0°	13.718	13.134	16.459	16.621	12.167	11.598
				90°	13.872	13.004	16.405	13.099	10.254	11.373
			1 Hz	0°	13.578	13.126	16.182	14.972	11.620	12.032
				90°	13.873	12.936	16.560	15.173	10.054	11.789
			Average		13.792	13.273	16.318	15.521	10.890	11.772

Unit: $\times 10^3$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.31459E+12	2.62918E+11	93.89	0.0001
CYCLE	2	1.63701E+09	8.18506E+08	0.29	0.7489
DEGREE	1	2.47223E+10	2.47223E+10	8.83	0.0062

R-Square = 0.947

Duncan Grouping	Mean	N	Degree
A	1385622	18	0
B	1333211	18	90

Note: Means with the same letter are not significantly different. (Alpha= 0.05)

Table E.1 -- Continued

GTR-80 modified AC-30 @ 25°C (77°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.567	2.594	2.598	2.598	2.825	2.555
Resilient Modulus	Instantaneous	Cycle Frequency	0.33 Hz	0°	9.323	9.365	12.156	12.974	9.399	9.294
				90°	9.313	9.836	12.172	12.583	9.483	9.902
			0.50 Hz	0°	8.978	9.182	12.348	12.602	9.261	9.338
				90°	9.280	9.466	11.778	12.458	9.408	9.560
			1 Hz	0°	8.848	9.017	11.757	12.044	9.103	8.884
				90°	8.774	9.334	11.651	12.244	9.051	9.360
			Average		9.084	9.365	11.977	12.484	9.264	9.486
	Total		0.33 Hz	0°	4.126	4.781	8.071	8.165	4.587	4.869
				90°	4.274	5.004	7.825	8.318	4.615	4.852
			0.50 Hz	0°	4.284	4.821	8.076	8.170	4.412	4.883
				90°	4.328	4.938	7.905	8.283	4.832	4.869
			1 Hz	0°	4.409	4.954	8.195	8.431	4.736	4.958
				90°	4.401	4.946	7.942	8.222	4.674	4.929
			Average		4.303	4.907	8.002	8.265	4.643	4.893

Unit: x10^5 psi

Results of Anova

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	9.670772E+11	1.934155E+11	2918.54	0.0001
CYCLE	2	7.806552E+08	3.903276E+08	5.89	0.0075
DEGREE	1	8.801115E+06	8.801115E+06	0.13	0.7184

R-Square = 0.998

Duncan Grouping	Mean	N	CYCLE Frequency
A	589967	12	1
B	581625	12	0.5
B			
B	579058	12	0.33

Duncan Grouping	Mean	N	Degree
A	584044	18	0
A	583056	18	90

Note: Means with the same letter are not significantly different. (Alpha= 0.05)

Table D-1 -- Continued

SBR modified AC-30 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.540	2.558	2.554	2.587	2.545	2.575
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	17.442	17.534	19.900	21.533	15.524	16.581
				90°	15.560	15.099	20.146	20.085	15.840	15.474
			0.50 Hz	0°	17.315	16.229	19.613	21.159	15.694	16.334
				90°	15.612	14.853	20.688	19.634	15.935	14.788
			1 Hz	0°	17.515	13.998	19.391	21.606	15.733	16.808
				90°	15.603	12.093	19.636	19.776	15.656	16.348
			Average		*16.508*	*14.960*	*19.896*	*20.616*	*15.730*	*16.066*
	Total		0.33 Hz	0°	13.533	11.949	16.338	18.509	11.924	12.424
				90°	12.223	11.487	17.352	17.989	11.989	12.403
			0.50 Hz	0°	13.536	11.771	16.213	18.999	11.897	12.988
				90°	12.374	11.317	17.652	17.125	11.932	11.969
			1 Hz	0°	13.771	12.399	16.874	18.663	11.949	12.887
				90°	12.522	11.931	16.777	17.328	12.050	12.836
			Average		*12.993*	*11.804*	*16.818*	*18.102*	*11.954*	*12.581*

Unit: x10^5 psi

Results of ANOVA

```
Source       DF    Anova SS          Mean Square    F Value     Pr > F
ASPHALT      5     2.20640E+12       4.41281E+11     174.23     0.0001
CYCLE        2     1.77135E+09       8.85674E+08       0.35     0.7080
DEGREE       1     1.40304E+10       1.40304E+10       5.54     0.0261
R-Square = 0.978

Duncan        Mean      N  Degree
Grouping
A             1424022   18  0

B             1384539   18  90
```

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table D-1 -- Continued

SBR modified AC-30 @ 25°C (77°F)

					No aging		FC oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.557	2.563	2.636	2.561	2.569	2.580
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	10.262	10.574	14.813	15.224	11.263	14.054
				90°	11.560	10.821	13.986	15.846	11.466	13.840
			0.50 Hz	0°	9.554	10.891	14.773	15.346	10.065	13.422
				90°	11.212	10.409	15.048	15.539	11.444	12.566
			1 Hz	0°	10.184	10.243	14.151	15.566	10.411	12.930
				90°	10.745	10.308	14.616	15.327	11.311	12.561
			Average		10.650	10.541	14.565	15.475	10.993	13.264
	Total		0.33 Hz	0°	6.242	6.175	10.256	10.738	5.514	6.264
				90°	6.408	6.111	10.316	11.336	6.500	6.663
			0.50 Hz	0°	6.070	6.306	10.549	10.834	5.594	6.408
				90°	6.449	6.138	10.516	11.192	6.484	6.558
			1 Hz	0°	6.100	6.256	10.531	10.969	5.662	6.684
				90°	6.423	6.155	10.541	11.217	6.661	6.633
			Average		6.265	6.190	10.452	11.053	6.103	6.587

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	6	1.61169E+12	2.22338E+11	775.01	0.0001
CYCLE	2	1.58122E+08	7.90610E+08	1.90	0.1689
DEGREE	1	8.25372E+09	8.25372E+09	19.84	0.0001

R-Square = 0.993

Duncan Grouping	Mean	N	Degree
A	792961	18	90
B	762678	18	0

Note: Means with the same letter are not significantly different. (Alpha= 0.05)

Table D 1 -- Continued

EVA modified AC-30 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.523	2.535	2.533	2.524	2.571	2.561
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	23.901	22.612	24.597	24.257	18.373	20.349
				90°	22.662	20.843	23.962	23.752	19.289	18.575
			0.50 Hz	0°	23.650	20.767	24.092	25.170	18.652	19.821
				90°	23.129	20.676	25.241	24.026	19.007	18.652
			1 Hz	0°	23.200	21.046	23.150	23.667	17.973	18.241
				90°	21.245	20.964	23.031	23.547	20.020	18.637
			Average		*22.965*	*21.151*	*24.012*	*24.070*	*18.886*	*19.143*
	Total		0.33 Hz	0°	19.808	17.602	20.711	20.454	14.326	13.784
				90°	18.189	16.509	20.575	20.111	15.752	13.274
			0.50 Hz	0°	19.846	17.858	20.597	20.738	14.597	14.209
				90°	18.199	16.925	20.722	20.432	15.655	14.102
			1 Hz	0°	19.867	17.781	20.543	20.562	14.716	14.389
				90°	18.077	16.928	20.396	20.489	16.004	14.187
			Average		*18.565*	*17.281*	*20.591*	*20.451*	*15.174*	*14.048*

Unit $\times 10^3$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.22744E+12	4.45489E+11	160.10	0.0001
CYCLE	2	2.55079E+09	1.27540E+09	0.46	0.6372
DEGREE	1	7.23067E+09	7.23067E+09	2.60	0.1186

R-Square = 0.968

Table 6.1 -- Continued

EVA modified AC-30 @ 25°C (77°F)

					No aging		FS oven 90 days		Roof 6 months	
			Spec #		02	04	07	08	11	12
			Height (in.)		2.630	2.624	2.626	2.543	2.577	2.663
Resilient Modulus	Instantaneous	Cycle frequency	0.32 Hz	0°	12.189	13.898	18.267	19.668	12.961	12.469
				90°	13.257	12.452	17.481	19.728	14.738	12.862
			0.50 Hz	0°	12.668	12.422	17.666	20.061	12.481	13.228
				90°	12.225	12.475	17.720	19.236	14.671	13.727
			1 Hz	0°	12.236	12.684	17.691	20.478	12.946	13.106
				90°	12.918	12.321	17.778	20.145	14.679	12.224
			Average		12.721	12.844	17.751	16.866	14.068	13.430
	Total		0.32 Hz	0°	7.528	8.215	12.378	13.288	7.729	8.181
				90°	7.960	7.696	12.868	16.602	8.764	8.027
			0.50 Hz	0°	7.664	8.602	12.726	14.012	7.852	8.460
				90°	8.148	7.869	13.661	16.286	8.790	8.166
			1 Hz	0°	7.669	8.551	12.270	14.878	7.631	8.608
				90°	8.167	8.006	13.815	15.488	8.859	8.285
			Average		7.999	8.174	13.287	14.756	8.321	8.288

Unit: $\times 10^5$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.81481E+12	5.52662E+11	266.66	0.0001
CYCLE	2	7.60249E+06	2.80126E+06	1.72	0.1971
DEGREE	1	2.12676E+10	2.12576E+10	9.65	0.0044

R-Square = 0.980

Duncan Grouping	Mean	N	CYCLE Frequency
A	1030842	12	1
A			
A	1006462	12	0.5
A			
A	666600	12	0.32

Duncan Grouping	Mean	N	Degree
A	1036244	18	90
B	687646	18	0

Note: Means with the same letter are not significantly different.
(Alpha= 0.05)

Table 9.2 -- Continued

EVA modified AC-20 @ 5°C (41°F)

					No Aging		FD oven 90 days		Roof 5 months	
			Spec #		01	02	05	05	08	10
			Height (in.)		2.555	2.541	2.551	2.570	2.571	2.551
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	17.246	18.860	19.090	21.431	21.329	21.540
				90°	17.522	20.255	16.579	20.722	20.989	21.450
			0.50 Hz	0°	17.724	18.991	24.174	21.556	18.525	23.177
				90°	18.072	20.119	19.494	20.854	18.158	21.303
			1 Hz	0°	17.543	18.701	23.364	21.448	18.815	21.304
				90°	17.549	20.087	21.423	20.754	20.474	21.394
			Average		17.593	19.502	20.821	21.128	19.683	21.695
	Total		0.33 Hz	0°	13.169	14.524	18.674	18.643	17.115	18.938
				90°	13.921	16.041	16.420	17.563	15.549	17.090
			0.50 Hz	0°	13.497	14.937	20.385	18.595	14.663	18.955
				90°	14.372	16.264	13.055	17.319	13.859	17.056
			1 Hz	0°	13.859	15.020	20.593	19.325	15.145	18.900
				90°	14.488	16.525	18.470	17.755	16.539	17.114
			Average		13.884	15.585	17.941	18.185	15.468	18.011

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	9.34159E+11	1.86832E+11	9.95	0.0001
CYCLE	2	5.07353E+10	2.53592E+10	1.35	0.2758
DEGREE	1	5.79285E+10	5.79285E+10	3.09	0.0903

Table E-1 -- Continued

EVA modified AC-20 @ 25°C (77°F)

				No aging		FD oven 90 days		Roof 6 months	
		Spec #		03	04	07	08	11	12
		Height (in.)		2.587	2.560	2.567	2.567	2.550	2.530
Resilient Modulus	Instantaneous	Cycle Frequency 0.33 Hz	0°	12.324	12.719	17.882	19.383	11.797	11.896
			90°	12.879	12.398	18.338	18.584	13.050	12.264
		0.50 Hz	0°	12.439	12.733	17.229	18.832	11.739	11.689
			90°	12.791	12.616	15.324	19.224	12.452	12.007
		1 Hz	0°	12.834	12.354	18.892	19.378	11.674	11.403
			90°	12.569	12.149	18.558	18.880	12.062	11.902
		Average		*12.564*	*12.455*	*16.720*	*19.044*	12.129	12.460
	Total	0.33 Hz	0°	7.881	7.817	12.587	13.241	6.670	7.046
			90°	7.950	7.384	11.873	14.518	7.170	7.184
		0.50 Hz	0°	7.760	7.902	12.786	13.549	6.707	7.197
			90°	7.925	7.554	11.926	14.392	7.178	7.207
		1 Hz	0°	7.853	7.643	12.506	13.540	6.873	7.298
			90°	7.995	7.624	11.923	14.418	7.188	7.237
		Average		*7.844*	*7.651*	*12.280*	*13.942*	6.948	*7.261*

Unit: $\times 10^5$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.70493e+12	5.40985e+11	494.47	0.0001
CYCLE	2	9.49361E+08	4.74680E+08	0.43	0.6524
DEGREE	1	9.50694E+08	9.50694E+08	0.87	0.3595

R-Square = 0.989

Table B.1 — Continued

EVA modified AC-5 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Weight (lb.)		2.532	2.533	2.543	2.543	2.583	2.559
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	14.535	16.650	21.371	17.537	15.185	16.708
				90°	15.557	17.285	20.323	20.185	15.834	15.105
			0.50 Hz	0°	14.782	16.505	21.342	19.877	14.819	17.228
				90°	15.825	17.668	20.383	15.707	12.399	15.624
			1 Hz	0°	14.554	16.659	21.311	19.333	14.767	16.710
				90°	16.035	16.685	20.440	20.113	15.416	16.890
			Average		15.288	16.523	20.862	19.326	14.737	16.211
	Total		0.33 Hz	0°	12.327	12.859	18.569	16.244	11.643	13.351
				90°	12.597	13.743	17.369	16.562	12.220	12.888
			0.50 Hz	0°	12.188	13.626	18.409	16.715	11.645	13.429
				90°	12.640	13.121	17.351	16.369	12.124	12.966
			1 Hz	0°	12.044	13.807	18.467	16.803	11.742	13.484
				90°	12.833	13.948	17.550	16.417	12.480	13.813
			Average		12.440	13.517	17.953	16.517	11.978	13.389

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.73750E+12	3.47499E+11	235.17	0.0001
CYCLE	2	2.45974E+09	1.22987E+09	0.85	0.4403
DEGREE	1	3.76360E+08	3.76360E+08	0.26	0.6170

R-Square = 0.978

Table C.1 -- Continued

EVA modified AC-5 @ 25°C (77°F)

					No aging		PU oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.500	2.631	2.626	2.620	2.600	2.510
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	8.770	10.017	14.074	14.446	9.927	10.271
				90°	9.402	10.158	13.845	15.048	9.033	10.001
			0.50 Hz	0°	9.997	9.294	14.380	13.803	8.734	8.742
				90°	8.318	10.034	13.729	16.761	8.639	9.787
			1 Hz	0°	10.013	9.126	13.692	14.392	9.354	8.676
				90°	9.384	9.678	13.310	15.018	8.646	9.248
			Average		9.647	9.701	13.856	14.761	9.206	9.799
	Total		0.33 Hz	0°	6.160	6.040	9.541	10.585	6.135	6.087
				90°	6.718	6.151	10.028	11.115	5.327	6.021
			0.60 Hz	0°	6.146	5.934	9.811	10.508	6.042	6.091
				90°	6.742	6.145	10.181	10.970	6.274	6.969
			1 Hz	0°	6.169	5.897	10.158	10.767	6.063	6.127
				90°	6.870	6.158	10.151	11.140	6.282	6.961
			Average		5.967	6.056	9.992	10.884	5.888	6.042

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.63844E+12	3.27688E+11	468.33	0.0001
CYCLE	2	3.68216E+08	1.84108E+08	0.27	0.7621
DEGREE	1	3.76350E+08	3.76350E+08	0.58	0.4804

R-Square = 0.989

Table C.1 -- Continued

SBBS modified AC-30 @ 5°C (41°F)

					No aging		PD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.548	2.636	2.551	2.666	2.562	2.581
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	19.875	23.379	22.851	23.040	20.779	15.912
				90°	17.883	21.021	22.585	21.811	21.086	18.909
			0.50 Hz	0°	21.132	22.289	22.872	23.640	21.019	18.638
				90°	20.782	21.110	20.403	21.896	21.448	18.973
			1 Hz	0°	23.154	23.078	21.920	23.809	20.819	18.548
				90°	20.406	22.886	20.514	22.293	20.268	19.029
			Average		*20.872*	*22.159*	*21.724*	*22.615*	*20.903*	*18.335*
	Total		0.33 Hz	0°	19.243	19.754	19.959	19.599	16.988	15.557
				90°	16.929	18.793	18.819	18.822	17.498	15.841
			0.50 Hz	0°	18.784	19.680	18.777	19.518	17.376	15.831
				90°	17.812	18.713	18.449	18.709	17.732	15.899
			1 Hz	0°	18.873	20.057	18.639	19.720	17.094	15.738
				90°	17.706	19.102	17.549	18.975	17.287	16.014
			Average		*18.241*	*19.350*	*18.873*	*19.224*	*17.331*	*15.830*

Unit: $x10^5$ psi

Results of ANOVA

```
Source      DF    Anova SS         Mean Square    F Value      Pr > F
ASPHALT     5     5.44931E+11      1.08986E+11      35.44      0.0001
CYCLE       2     1.50354E+09      7.51772E+08       0.24      0.7848
DEGREE      1     2.69233E+10      2.69233E+10       8.76      0.0064

R-Square = 0.876

Duncan        Mean      N    Degree
Grouping
A             1842483   18   0

B             1707709   18   90
         Note: Means with the same letter are not significantly different.
               (Alpha= 0.05)
```

Table D.1 — Continued

SEBS modified AC-30 @ 25°C (77°F)

					No aging		PD oven 90 Days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Weight (lb.)		2.530	2.535	2.560	2.545	2.526	2.552
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	15.025	14.251	16.251	17.744	15.187	15.940
				90°	15.599	15.372	16.415	16.897	15.965	15.143
			0.50 Hz	0°	14.655	14.140	16.041	16.829	15.231	15.429
				90°	14.521	14.961	16.893	17.286	15.524	15.101
			1 Hz	0°	15.135	14.068	16.457	17.906	15.220	16.009
				90°	15.685	14.593	17.153	17.365	14.762	15.056
			Average		15.103	14.632	16.525	17.222	15.218	15.446
	Total		0.33 Hz	0°	10.122	9.061	12.396	12.665	10.574	9.999
				90°	9.922	9.553	11.910	12.457	10.087	10.180
			0.50 Hz	0°	10.298	9.372	12.281	13.220	10.597	10.401
				90°	10.005	9.757	12.399	12.649	10.093	10.281
			1 Hz	0°	10.756	9.269	12.343	13.420	10.928	10.695
				90°	10.188	9.782	12.813	12.779	9.974	10.380
			Average		10.215	9.422	12.322	12.864	10.276	10.224

Unit: x10^{5} psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	5.46348E+11	1.09270E+11	152.33	0.0001
CYCLE	2	8.91422E+09	4.45711E+09	6.21	0.0060
DEGREE	1	2.14369E+09	2.14369E+09	2.99	0.0953

R-Square = 0.966

```
Duncan      Mean      N  CYCLE        | Duncan       Mean     N   Degree
Grouping                 Frequency    | Grouping
A           1111131   12  1           | A            1099944  18  0
A                                     | A
A    B      1092942   12  0.50        | A            1084511  18  90
     B
     B      1072608   12  0.33
```

Note: Means with the same letter are not significantly different. (Alpha= 0.05)

Table 0-1 -- Continued

SEBS modified AC-20 @ 5°C (41°F)

					No aging		TD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.569	2.561	2.569	2.562	2.572	2.551
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	18.409	20.422	23.007	23.479	17.495	18.673
				90°	20.126	20.175	22.277	22.619	16.931	18.285
			0.50 Hz	0°	19.628	19.563	21.379	22.742	19.657	18.494
				90°	18.822	19.488	22.121	23.464	18.913	18.782
			1 Hz	0°	19.720	19.832	21.672	21.621	20.213	18.745
				90°	19.062	19.907	20.942	22.039	19.160	18.357
			Average		19.295	19.888	21.899	22.661	18.728	18.556
	Total		0.33 Hz	0°	15.639	16.347	18.778	18.303	15.236	15.838
				90°	16.088	16.252	19.268	18.404	14.913	15.635
			0.50 Hz	0°	16.190	16.261	18.400	18.403	16.197	15.601
				90°	15.344	16.165	19.026	18.036	15.750	15.391
			1 Hz	0°	16.202	16.099	19.632	18.380	16.203	15.572
				90°	15.608	16.649	18.022	18.114	15.965	15.375
			Average		15.845	16.286	18.838	18.273	15.717	15.568

Unit: x10^{5} psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	8.42001E+11	1.68400E+11	106.72	0.0001
CYCLE	2	4.92194E+08	2.46097E+08	0.16	0.8564
DEGREE	1	2.73180E+09	2.73180E+09	1.73	0.1993

R-Square = 0.952

Table C.1 -- Continued

SEBS modified AC-20 @ 25°C (77°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.551	2.552	2.531	2.575	2.564	2.551
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	12.419	12.716	17.147	18.666	12.508	12.666
				90°	13.042	12.833	16.520	17.872	12.319	12.018
			0.50 Hz	0°	12.258	12.245	16.071	17.222	12.486	12.512
				90°	13.357	12.655	15.371	17.616	12.268	11.912
			1 Hz	0°	11.996	12.466	17.014	17.674	11.358	12.264
				90°	12.482	12.481	16.239	17.758	11.665	11.697
			Average		12.566	12.567	16.394	17.746	12.254	12.167
	Total		0.33 Hz	0°	7.487	7.384	12.264	14.183	7.507	7.647
				90°	8.231	7.685	12.247	13.665	7.368	7.107
			0.50 Hz	0°	7.597	7.440	12.317	12.991	7.532	7.547
				90°	8.356	7.757	12.063	13.829	7.384	7.134
			1 Hz	0°	7.676	7.655	12.514	13.307	7.457	7.623
				90°	8.312	7.828	12.360	13.825	7.328	7.156
			Average		7.943	7.647	12.316	13.633	7.429	7.353

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.38158E+12	4.76317E+11	574.31	0.0001
CYCLE	2	7.36736E+08	3.68368E+08	0.45	0.6448
DEGREE	1	6.68222E+08	6.68222E+08	0.81	0.3773

R-Square = 0.951

Table 8.1 -- Continued

SEBS modified AC-5 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Weight (in.)		2.542	2.557	2.550	2.565	2.545	2.558
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	15.065	14.114	17.281	18.460	15.315	15.910
				90°	13.690	13.349	17.065	18.277	14.519	15.030
			0.50 Hz	0°	15.010	13.618	17.596	18.183	14.964	16.624
				90°	14.494	13.249	17.220	18.107	14.183	15.824
			1 Hz	0°	14.375	13.815	17.452	17.783	14.897	16.840
				90°	14.095	12.653	17.508	18.135	14.086	14.545
			Average		14.455	13.466	17.354	18.158	14.661	15.788
	Total		0.33 Hz	0°	11.319	10.395	15.132	15.532	11.563	13.625
				90°	10.651	11.124	14.557	15.316	11.327	13.657
			0.50 Hz	0°	11.710	10.591	15.251	15.589	11.694	13.219
				90°	10.446	9.781	14.565	15.451	11.385	12.285
			1 Hz	0°	11.393	10.903	15.117	15.485	11.748	13.569
				90°	10.638	10.156	14.853	15.684	11.406	13.744
			Average		10.976	10.475	14.929	15.510	11.539	12.667

Unit: $\times 10^5$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.32792E+12	2.65583E+11	186.04	0.0001
CYCLE	2	6.25839E+07	3.12919E+07	0.02	0.9783
DEGREE	1	3.06250E+10	3.06250E+10	21.45	0.0001

R-Square = 0.972

Duncan Grouping	Mean	N	Degree
A	1297422	18	0
B	1239089	18	90

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 0.1 -- Continued

SEBS modified AC-5 @ 25°C (77°F)

					No aging		FD oven 90 Days		Roof 6 months	
			Spec 6		03	04	07	08	11	12
			Height (in.)		2.556	2.549	2.550	2.556	2.534	2.612
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	7.951	8.241	13.339	13.326	8.856	9.860
				90°	8.292	7.877	13.894	14.533	8.687	8.750
			0.50 Hz	0°	8.038	7.945	13.040	12.519	8.725	9.307
				90°	8.050	7.874	13.253	13.758	8.598	8.749
			1 Hz	0°	7.775	7.824	12.880	12.896	8.256	8.632
				90°	7.891	7.785	13.546	14.020	8.209	8.475
			Average		8.000	7.938	13.299	13.509	8.562	8.962
	Total		0.33 Hz	0°	4.285	4.330	9.284	8.481	4.817	4.879
				90°	4.432	4.602	9.601	9.333	4.905	4.732
			0.50 Hz	0°	4.392	4.397	9.395	8.868	4.944	4.935
				90°	4.399	4.547	8.907	9.625	4.852	4.777
			1 Hz	0°	4.465	4.459	9.716	9.067	5.001	4.988
				90°	4.460	4.562	10.166	9.684	4.845	4.818
			Average		4.406	4.466	9.678	9.175	4.894	4.855

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	6	1.84052E+12	3.68104E+11	886.96	0.0001
CYCLE	2	2.91443E+09	1.45721E+09	3.51	0.0441
DEGREE	1	3.31392E+09	3.31392E+09	7.99	0.0088

R-Square = 0.994

Duncan Grouping		Mean	N	CYCLE Frequency
A		636176	12	1
A				
A	B	625317	12	0.50
	B			
	B	613176	12	0.33

Duncan Grouping	Mean	N	Degree
A	634150	18	90
B	614961	18	0

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table D.2 Results of resilient modulus tests on open-graded mixtures

Unmodified AC-30 @ 5°C (41°F)

				No aging		FD oven 90 days		Roof 6 months	
		Spec #		01	02	05	06	09	10
		Height (in.)		2.453	2.534	2.578	2.533	2.538	2.546
Resilient Modulus	Instantaneous	Cycle frequency 0.33 Hz	0°	11.147	13.847	16.541	16.327	13.486	14.738
			90°	11.198	13.667	16.391	17.282	12.494	14.292
		0.50 Hz	0°	12.330	13.644	14.907	16.517	13.512	13.943
			90°	11.193	12.064	13.655	16.853	12.568	14.638
		1 Hz	0°	11.940	13.136	15.711	16.836	13.365	13.428
			90°	10.674	12.732	16.140	14.991	12.186	13.634
		Average		*11.339*	*13.182*	*15.557*	*16.268*	*12.935*	*14.112*
	Total	Cycle frequency 0.33 Hz	0°	8.956	9.916	11.873	12.191	9.479	10.029
			90°	8.746	9.464	11.156	12.161	9.400	10.117
		0.50 Hz	0°	8.908	9.736	12.082	11.673	9.879	10.209
			90°	8.561	8.933	10.849	12.044	9.243	10.606
		1 Hz	0°	9.208	9.816	11.853	12.043	9.986	10.308
			90°	8.625	9.886	11.478	11.681	9.449	10.044
		Average		*8.841*	*9.626*	*11.565*	*11.966*	*9.585*	*10.219*

Unit: x10^5 psi

Results of ANOVA

```
Source       DF     Anova SS          Mean Square     F Value      Pr > F
--------------------------------------------------------------------------
ASPHALT      5      4.47707E+11       8.95414E+10     113.95       0.0001
CYCLE        2      1.05361E+09       5.26804E+08       0.67       0.5197
DEGREE       1      9.62613E+09       9.62613E+09      12.25       0.0016
--------------------------------------------------------------------------
R-Square = 0.986

Duncan        Mean       N   Degree
Grouping
A             1046543    18   0

B             1013839    18   90
```

Note: Means with the same letter are not significantly different. (Alpha= 0.05)

Table D.2 -- Continued

Unmodified AC-30 @ 25°C (77°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Weight (in.)		2.559	2.555	2.515	2.537	2.604	2.535
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	7.863	7.965	11.757	9.766	7.953	8.542
				90°	6.984	8.969	12.405	10.739	9.443	9.100
			0.50 Hz	0°	6.685	9.073	12.351	9.642	8.343	9.599
				90°	7.504	9.461	11.039	10.077	9.052	10.161
			1 Hz	0°	8.708	9.023	12.114	9.444	8.237	8.974
				90°	7.278	8.227	13.718	10.882	8.365	9.739
			Average		7.216	9.160	12.256	10.081	8.566	9.362
	Total		0.33 Hz	0°	4.045	4.598	6.322	5.781	4.622	4.835
				90°	3.833	5.020	6.656	4.162	5.081	4.980
			0.50 Hz	0°	3.851	4.631	6.522	6.463	4.556	5.243
				90°	4.015	4.722	6.171	6.642	4.545	4.988
			1 Hz	0°	3.839	4.867	5.547	6.291	4.777	5.275
				90°	4.017	4.516	6.249	6.517	5.028	5.171
			Average		3.933	4.742	6.318	6.192	4.837	5.062

Unit: $\times 10^3$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.51572E+11	5.03143E+10	142.32	0.0001
CYCLE	2	1.21888E+09	5.09439E+08	1.72	0.1974
DEGREE	1	6.95389E+07	6.95389E+07	0.20	0.6609

R-Square = 0.963

Table C.2 -- Continued

Elvaloy-modified AC-30 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 5 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.478	2.481	2.505	2.520	2.539	2.527
Resilient Modulus	Instantaneous	Cycle Frequency	0.33 Hz	0°	14.822	13.493	15.063	14.836	15.055	13.948
				90°	14.936	14.719	14.778	15.889	15.327	13.338
			0.50 Hz	0°	14.787	13.913	14.572	15.056	16.633	14.985
				90°	15.252	14.209	15.656	16.288	14.138	13.865
			1 Hz	0°	16.514	15.112	14.994	14.236	14.490	14.609
				90°	15.398	15.126	14.793	15.529	14.204	14.937
			Average		15.203	14.428	15.109	15.139	14.979	14.101
	Total		0.33 Hz	0°	11.133	10.397	11.506	11.465	11.201	10.299
				90°	11.235	10.854	11.260	11.405	11.546	10.289
			0.50 Hz	0°	11.369	10.994	11.378	11.483	12.045	10.508
				90°	11.451	10.365	12.518	11.674	11.086	10.398
			1 Hz	0°	11.942	10.786	12.125	11.029	11.218	10.832
				90°	11.953	10.970	11.821	11.757	11.318	10.314
			Average		11.912	10.728	11.751	11.471	11.462	10.423

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	8.04295E+10	1.60857E+10	15.09	0.0001
CYCLE	2	4.69437E+09	2.34718E+09	2.20	0.1301
DEGREE	1	3.96010E+06	3.96010E+06	0.00	0.9519

R-Square = 0.747

Table E.2 -- Continued

Gilsonite modified AC-30 @ 25°C (77°F)

					No aging		FD oven 60 days		Roof 5 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.496	2.601	2.494	2.628	2.607	2.607
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	9.363	8.261	11.506	12.676	8.422	8.963
				90°	10.626	8.883	13.636	14.186	9.133	6.260
			0.50 Hz	0°	10.276	9.680	11.366	12.123	8.602	6.875
				90°	9.902	9.494	12.194	10.278	8.920	6.197
			1 Hz	0°	6.976	8.966	11.300	12.512	9.246	8.385
				90°	10.662	6.460	11.312	12.779	9.842	9.339
			Average		*10.102*	*9.112*	*11.958*	*12.807*	*9.074*	*9.008*
	Total		0.33 Hz	0°	6.686	6.121	7.609	6.708	5.206	5.416
				90°	6.616	5.532	7.854	7.012	6.439	6.927
			0.50 Hz	0°	5.736	6.664	7.262	7.108	6.443	5.666
				90°	6.866	6.626	7.351	6.353	5.441	5.505
			1 Hz	0°	5.902	5.788	7.478	7.021	6.448	6.846
				90°	6.769	6.401	7.242	6.853	5.623	5.369
			Average		*5.772*	*5.504*	*7.466*	*6.844*	*5.433*	*5.621*

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	6	2.13412E+11	4.26824E+10	86.60	0.0001
CYCLE	2	3.07250E+08	1.53626E+08	0.32	0.7269
DEGREE	1	4.63541E+06	4.63541E+06	0.01	0.9226

R-Square = 0.943

Table C.2 -- Continued

Carbon black modified AC-30 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Weight (lb.)		2.552	2.522	2.522	2.458	2.534	2.527
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	12.409	12.978	15.149	15.843	14.276	12.349
				90°	12.450	13.043	15.108	13.756	13.909	13.047
			0.50 Hz	0°	12.741	12.455	16.435	13.631	14.637	12.602
				90°	12.120	13.011	14.640	15.283	13.408	13.779
			1 Hz	0°	11.491	12.823	14.060	14.348	13.108	12.629
				90°	12.397	12.666	13.989	14.698	13.876	12.095
			Average		12.101	12.825	14.697	14.612	13.669	12.750
	Total		0.33 Hz	0°	9.060	9.547	11.571	10.620	10.505	9.464
				90°	8.708	9.381	10.857	11.364	10.214	9.373
			0.50 Hz	0°	8.919	9.173	11.351	10.455	10.494	9.532
				90°	8.766	9.544	11.111	11.339	10.397	9.509
			1 Hz	0°	8.917	9.453	10.708	10.616	9.883	9.676
				90°	8.931	9.385	10.598	11.252	10.327	9.283
			Average		8.883	9.414	11.033	10.941	10.383	9.473

Unit: x10^{5} psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.34775E+11	4.69551E+10	63.48	0.0001
CYCLE	2	1.42620E+09	7.13102E+08	0.96	0.3940
DEGREE	1	4.47472E+07	4.47472E+07	0.06	0.8076

R-Square = 0.922

Table 0.2 -- Continued

Carbon black modified AC-30 @ 25°C (77°F)

					No aging		PD oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Weight (lb)		2.522	2.512	2.515	2.537	2.823	2.523
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	8.261	9.155	9.589	9.955	8.888	9.223
				90°	8.113	9.526	11.758	11.616	7.499	7.896
			0.50 Hz	0°	9.195	8.505	10.586	10.272	9.564	9.867
				90°	10.595	8.544	9.587	11.677	7.684	9.559
			1 Hz	0°	9.697	7.820	10.148	10.705	8.095	8.815
				90°	10.995	7.896	11.188	11.179	7.781	5.663
			Average		8.557	8.622	10.478	11.491	8.403	9.088
	Total		0.33 Hz	0°	4.651	4.834	5.949	6.348	5.757	4.845
				90°	5.647	4.898	5.620	6.552	4.512	4.598
			0.50 Hz	0°	4.684	5.887	6.185	6.205	4.736	5.227
				90°	4.839	5.721	5.776	8.207	4.833	5.072
			1 Hz	0°	4.617	4.727	5.562	5.184	5.008	5.008
				90°	5.021	4.790	5.708	6.453	5.781	5.221
			Average		4.745	5.775	5.867	8.366	4.769	4.984

Unit: $\times 10^3$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.35293E+11	2.72587E+10	55.52	0.0001
CYCLE	2	8.77877E+08	4.38939E+08	1.54	0.2330
DEGREE	1	5.27502E+07	5.27502E+07	0.23	0.6429

R-Square = 0.947

Table D.2 -- Continued

GTR-80 modified AC-30 @ 5°C (41°F)

					No aging		PD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.437	2.354	2.455	2.459	2.478	2.460
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	11.734	15.529	15.978	15.536	14.801	15.685
				90°	14.685	15.710	14.313	16.412	14.574	14.970
			0.50 Hz	0°	12.677	16.124	16.476	15.638	13.526	14.757
				90°	11.429	17.576	14.780	15.164	15.332	13.672
			1 Hz	0°	13.163	15.355	15.918	15.008	13.006	15.710
				90°	13.113	15.166	13.759	16.794	15.538	13.826
			Average		*12.899*	*15.918*	*15.204*	*15.575*	*14.529*	*14.776*
	Total		0.33 Hz	0°	9.898	11.245	11.543	11.866	10.136	10.687
				90°	10.472	11.471	11.073	11.863	10.824	10.560
			0.50 Hz	0°	10.302	14.209	11.659	11.642	9.575	10.554
				90°	10.288	12.176	10.484	11.382	10.289	10.836
			1 Hz	0°	10.034	11.545	11.654	12.160	9.560	10.762
				90°	10.465	12.076	11.437	11.610	10.155	11.270
			Average		*10.244*	*11.786*	*11.312*	*11.751*	*10.223*	*10.865*

Unit: $\times 10^5$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.53036E+11	3.06075E+10	13.21	0.0001
CYCLE	2	1.49715E+09	7.48754E+08	0.26	0.7755
DEGREE	1	3.35158E+08	3.35158E+08	0.11	0.7375

R-Square = 0.712

Table D.2 -- Continued

GTR-80 modified AC-30 @ 25°C (77°F)

					No aging		FO oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Weight (lb.)		2.436	2.455	2.464	2.458	2.465	2.474
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	8.862	9.327	11.295	11.317	8.710	9.636
				90°	8.597	8.762	10.939	13.247	9.458	9.343
			0.50 Hz	0°	9.150	8.761	8.585	10.725	9.405	10.168
				90°	9.567	8.075	9.741	11.098	9.605	9.376
			1 Hz	0°	9.494	8.785	9.226	11.262	8.041	11.069
				90°	8.787	8.971	9.355	11.151	10.545	11.366
			Average		9.078	8.780	9.858	11.488	9.294	10.159
	Total		0.33 Hz	0°	5.259	4.855	6.487	7.141	4.716	5.307
				90°	4.808	4.997	6.181	6.676	5.430	5.371
			0.50 Hz	0°	5.162	4.985	6.709	6.930	5.241	5.722
				90°	5.055	4.796	6.684	7.064	5.658	5.242
			1 Hz	0°	5.306	5.074	6.707	7.063	5.243	5.639
				90°	4.967	4.668	6.515	6.811	5.663	5.472
			Average		5.093	4.879	6.547	6.952	5.308	5.459

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.12199E+11	4.24397E+10	104.47	0.0001
CYCLE	2	2.23366E+09	1.11683E+09	2.75	0.0819
DEGREE	1	8.04592E+08	8.04592E+08	1.98	0.1707

R-Square = 0.952

Table 8.2 -- Continued

SBR modified AC-30 @ 5°C (41°F)

					No aging		FO oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.457	2.469	2.463	2.457	2.496	2.472
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	13.000	12.768	8.069	15.068	14.407	12.790
				90°	12.614	13.406	14.594	15.401	13.340	14.309
			0.50 Hz	0°	12.188	12.704	14.074	14.210	12.907	12.394
				90°	13.159	12.640	13.971	14.495	12.635	13.372
			1 Hz	0°	12.243	13.082	14.169	14.147	12.959	12.264
				90°	12.962	14.069	14.461	14.516	12.968	13.539
			Average		12.699	13.111	13.223	14.654	13.204	13.111
	Total		0.33 Hz	0°	9.530	9.020	6.960	11.147	9.717	9.588
				90°	8.947	9.290	11.215	11.621	9.454	10.458
			0.50 Hz	0°	9.303	9.488	11.311	11.035	9.377	9.358
				90°	8.954	9.476	10.693	11.351	9.632	10.284
			1 Hz	0°	9.552	9.469	10.797	10.868	9.695	9.605
				90°	8.624	9.728	10.803	11.222	9.387	10.574
			Average		9.152	9.412	10.297	11.207	9.527	9.978

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.68226E+11	3.36653E+10	6.15	0.0006
CYCLE	2	6.63431E+09	3.31715E+09	0.61	0.5528
DEGREE	1	8.69416E+09	8.69416E+09	1.59	0.2184

R-square = 0.564

Table 0.2 -- continued

SBR modified AC-30 @ 25°C (77°F)

			No aging		FD oven 90 days		Roof 5 months	
	Spec #		03	04	07	08	11	12
	Weight (lb.)		2.464	2.441	2.502	2.534	2.496	2.515
Resilient Modulus, Instantaneous	Cycle frequency 0.33 Hz	0°	8.679	9.272	10.911	10.585	8.403	8.934
		90°	7.852	8.711	11.402	10.524	8.037	9.263
	0.50 Hz	0°	9.289	9.308	12.697	8.967	9.389	8.700
		90°	7.779	7.921	12.616	11.323	9.015	8.451
	1 Hz	0°	7.551	9.144	13.686	9.232	8.391	8.415
		90°	7.924	11.309	11.291	9.569	8.431	9.042
	Average		8.179	9.278	12.094	10.049	8.572	8.634
Resilient Modulus, Total	Cycle frequency 0.33 Hz	0°	4.148	4.725	5.795	5.876	4.575	4.299
		90°	3.850	4.911	6.521	6.394	4.605	4.785
	0.50 Hz	0°	4.622	5.038	5.153	6.098	4.709	4.924
		90°	4.124	5.029	6.573	6.256	4.589	4.453
	1 Hz	0°	4.401	5.215	6.103	6.362	4.679	4.946
		90°	4.136	5.444	6.677	6.096	4.590	4.824
	Average		4.197	5.060	6.325	6.204	4.658	4.690

Unit: x10^5 psi

Results of ANOVA

```
Source     DF     Anova SS         Mean Square     F Value      Pr > F

ASPHALT    5      2.28554E+11      4.57108E+10     98.54        0.0001
CYCLE      2      3.83424E+09      1.91712E+09      4.13        0.0272
DEGREE     1      5.67210E+08      5.67210E+08      1.22        0.2786

R-Square = 0.949

Duncan                 Mean         N   Cycle
Grouping

        A              528933       12  1
        A
B       A              520229       12  0.5
B
B                      504027       12  0.33

     Note: Means with the same letter are not significantly different
           (Alpha= 0.05)
```

Table 0.2 -- Continued

EVA modified AC-30 @ 5°C (41°F)

				No aging		FD oven 90 Days		Roof 6 months	
		Spec #		01	02	05	06	09	10
		Height (in.)		2.477	2.474	2.475	2.479	2.507	2.527
Resilient Modulus	Instantaneous	0.33 Hz	0°	14.618	14.701	14.981	16.803	12.945	12.657
			90°	14.777	14.943	15.379	13.454	13.257	12.304
		0.50 Hz	0°	14.261	16.637	15.626	15.948	13.426	8.350
			90°	14.686	14.420	14.675	14.768	13.936	12.380
		1 Hz	0°	14.612	15.159	14.796	16.336	15.001	12.012
			90°	15.561	14.428	14.434	14.854	13.559	11.716
		Average		14.752	15.072	14.982	15.361	13.688	11.720
	Total	0.33 Hz	0°	10.643	11.118	11.367	12.463	9.894	9.725
			90°	11.147	10.706	11.059	10.351	10.249	9.435
		0.50 Hz	0°	10.646	12.135	11.786	12.239	10.335	7.647
			90°	11.154	10.987	11.660	11.332	10.267	9.360
		1 Hz	0°	10.851	12.111	11.574	12.629	10.405	9.300
			90°	11.058	10.871	11.367	11.029	10.251	10.060
		Average		10.917	11.321	11.472	11.674	10.250	9.255

Cycle frequency

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.51352E+11	5.02704E+10	14.52	0.0001
CYCLE	2	4.45027E+09	2.22514E+09	0.64	0.5336
DEGREE	1	5.88624E+09	5.88624E+09	1.70	0.2032

R-Square = 0.737

Table C.2 -- Continued

EVA modified AC-30 @ 25°C (77°F)

					No aging		FL oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.431	2.609	2.501	2.501	2.531	2.521
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	9.952	9.471	9.282	12.635	10.869	9.568
				90°	11.582	9.371	10.929	14.165	8.882	10.229
			0.50 Hz	0°	10.302	8.948	10.469	15.577	8.483	10.363
				90°	11.594	8.439	11.226	12.483	8.506	8.527
			1 Hz	0°	9.247	7.800	10.593	11.256	5.801	10.162
				90°	11.469	9.387	12.555	10.589	10.005	10.213
			Average		10.691	8.903	11.137	12.785	9.459	9.844
	Total		0.33 Hz	0°	5.660	5.007	6.406	6.549	5.494	5.442
				90°	5.871	6.222	6.605	7.442	5.156	5.326
			0.50 Hz	0°	5.773	5.075	6.474	7.086	5.542	5.725
				90°	6.027	5.371	6.569	6.924	5.150	5.219
			1 Hz	0°	5.504	5.049	6.517	7.008	5.283	5.402
				90°	6.617	5.361	7.166	7.089	5.401	5.338
			Average		5.959	5.181	6.689	7.083	5.329	5.607

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	1.85707E+11	3.71415E+10	78.58	0.0001
CYCLE	2	8.81502E+08	4.40751E+08	0.94	0.4041
DEGREE	1	1.58567E+09	1.58967E+09	3.38	0.0770

R-Square = 0.937

Table D-2 -- Continued

EVA modified AC-20 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Weight (lb.)		2.499	2.510	2.514	2.520	2.478	2.521
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	12.604	12.291	13.224	14.345	15.126	12.107
				90°	12.044	11.782	14.966	15.130	14.205	12.620
			0.50 Hz	0°	12.862	12.544	13.294	14.503	13.843	11.859
				90°	11.421	11.035	15.316	15.382	13.774	11.963
			1 Hz	0°	12.223	12.936	14.776	13.382	13.156	12.019
				90°	11.372	10.706	15.143	14.373	13.177	12.557
			Average		12.221	11.882	14.498	14.529	13.885	12.268
	Total		0.33 Hz	0°	9.373	9.045	10.536	10.726	10.716	8.680
				90°	9.215	8.311	11.265	11.155	10.352	9.359
			0.50 Hz	0°	9.599	8.769	10.326	10.466	10.192	8.669
				90°	9.293	8.236	11.404	11.053	9.947	8.815
			1 Hz	0°	9.375	9.057	11.169	10.746	10.563	9.372
				90°	9.296	7.959	10.882	10.898	10.838	9.008
			Average		9.357	8.532	10.934	10.841	10.301	9.051

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.98638E+11	5.97276E+10	52.36	0.0001
CYCLE	2	1.44084E+09	7.20422E+08	0.63	0.5394
DEGREE	1	6.67714E+08	6.67714E+08	0.59	0.4509

R-Square = 0.907

Table C.2 -- Continued

EVA modified AC-20 @ 25°C (77°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.509	2.637	2.471	2.475	2.478	2.490
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	6.876	8.439	11.692	10.631	9.661	8.324
				90°	9.172	9.196	11.074	12.602	9.454	10.739
			0.60 Hz	0°	8.748	8.406	10.649	9.641	9.873	9.359
				90°	8.579	8.106	10.944	10.262	9.097	10.425
			1 Hz	0°	8.463	9.335	10.942	10.126	8.756	8.141
				90°	7.724	9.716	10.962	11.879	8.473	8.021
			Average		8.527	8.867	10.942	10.856	9.219	9.168
	Total		0.33 Hz	0°	4.113	4.401	6.293	6.372	4.614	4.198
				90°	4.646	4.283	6.965	6.918	4.663	4.616
			0.60 Hz	0°	4.331	4.412	6.078	6.299	4.697	4.311
				90°	4.482	4.315	6.309	6.420	4.650	4.664
			1 Hz	0°	4.241	4.336	6.336	6.284	4.769	4.356
				90°	4.407	4.689	6.616	6.849	4.913	4.469
			Average		4.353	4.401	6.507	6.524	4.701	4.419

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	6	3.81662E+11	7.63127E+10	66.15	0.0001
CYCLE	2	4.65826E+08	2.27914E+08	0.20	0.8219
DEGREE	1	1.32977E+09	1.32977E+09	1.16	0.2925

R-Square = 0.925

Table 0.2 — Continued

EVA modified AC-5 @ 5°C (41°F)

					No aging		FO oven 90 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.511	2.481	2.491	2.491	2.496	2.502
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	10.629	10.389	12.507	14.109	12.345	12.054
				90°	10.724	11.143	12.827	13.866	14.101	10.708
			0.50 Hz	0°	10.884	11.043	12.182	13.561	11.894	11.765
				90°	10.410	11.862	12.976	14.516	13.406	11.104
			1 Hz	0°	10.313	10.537	12.251	13.411	11.861	11.969
				90°	10.196	11.289	12.531	14.080	13.062	11.072
			Average		*10.526*	*11.044*	*12.546*	*13.924*	*12.778*	*11.458*
	Total		0.33 Hz	0°	7.687	7.680	9.359	10.582	9.029	8.956
				90°	7.017	7.079	9.677	10.872	10.012	7.861
			0.50 Hz	0°	7.593	7.804	9.427	10.403	9.042	8.968
				90°	7.285	7.690	9.673	11.072	9.788	7.885
			1 Hz	0°	7.732	7.907	9.443	10.313	9.117	9.032
				90°	7.476	7.051	9.969	10.776	9.539	8.102
			Average		*7.465*	*7.836*	*9.591*	*10.686*	*9.421*	*8.477*

Unit: x10^{5} psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	4.38519E+11	8.77038E+10	64.67	0.0001
CYCLE	2	1.72016E+08	8.60076E+07	0.06	0.9387
DEGREE	1	4.19639E+07	4.19639E+07	0.03	0.8616

R-Square = 0.923

Table C-2 -- Continued

EVA modified AC-5 @ 25°C (77°F)

					No aging		PD oven 50 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.498	2.515	2.446	2.480	2.494	2.485
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	7.437	6.845	9.209	9.869	6.433	7.531
				90°	6.634	6.649	9.579	8.643	6.910	7.203
			0.50 Hz	0°	6.579	6.838	10.486	10.836	7.589	7.173
				90°	6.808	6.377	9.273	9.456	7.713	8.383
			1 Hz	0°	6.602	6.873	8.686	9.510	7.329	6.528
				90°	6.611	6.245	8.643	8.791	7.342	6.760
			Average		6.848	6.638	9.366	9.568	7.216	6.929
	Total		0.33 Hz	0°	3.472	3.381	6.162	6.048	4.279	3.982
				90°	3.568	3.161	5.715	5.691	4.062	3.989
			0.50 Hz	0°	3.582	3.415	5.838	5.765	4.452	3.832
				90°	3.582	3.063	5.708	5.355	4.229	3.915
			1 Hz	0°	3.518	3.425	5.838	5.822	4.325	3.945
				90°	3.528	3.102	5.694	6.003	4.228	3.938
			Average		3.538	3.258	5.839	5.7754	4.263	3.947

Unit: $\times 10^5$ psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	3.72119E+11	7.44239E+10	412.75	0.0001
CYCLE	2	2.15597E+08	1.07799E+08	0.60	0.5571
DEGREE	1	1.95532E+09	1.95532E+09	10.85	0.0028

R-Square = 0.987

Duncan Grouping	Mean	N	DEGREE
A	450805	18	0
B	436166	18	90

Note: Means with the same letter are not significantly different. (Alpha= 0.05)

Table 0.3 -- Continued

SBBS modified AC-30 @ 5°C (41°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		01	03	09	06	09	10
			Height (in.)		3.489	3.536	2.558	2.525	2.519	2.516
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	15.328	13.853	14.133	16.134	13.809	14.171
				90°	14.576	12.397	15.119	16.189	14.379	13.119
			0.50 Hz	0°	14.656	13.039	14.689	14.599	13.994	11.639
				90°	14.103	13.943	15.692	14.793	13.930	13.996
			1 Hz	0°	14.023	12.378	14.749	14.943	13.798	13.704
				90°	15.633	14.324	15.040	14.773	14.112	13.561
			Average		**14.847**	**13.384**	**14.896**	**15.225**	**13.868**	**13.291**
	Total		0.33 Hz	0°	10.937	10.338	11.116	11.935	9.936	10.643
				90°	11.054	10.615	11.532	11.591	10.971	10.524
			0.50 Hz	0°	11.063	10.436	11.219	11.890	10.483	10.877
				90°	11.169	10.518	10.896	11.903	10.699	10.111
			1 Hz	0°	11.532	10.243	11.404	11.739	10.323	10.379
				90°	11.380	10.397	11.301	11.198	11.093	10.467
			Average		**11.186**	**10.388**	**11.244**	**11.583**	**10.584**	**10.499**

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	6.58086E+10	1.316171E+10	19.09	0.0001
CYCLE	2	8.35831E+08	4.179158E+08	0.48	0.6245
DEGREE	1	7.67105E+08	7.671053E+08	0.88	0.3567

R-Square = 0.876

Table C.2 -- Continued

SEBS modified AC-30 @ 25°C (77°F)

					No aging		FD oven 90 days		Roof 6 months	
			Spec #		03	04	07	08	11	12
			Height (in.)		2.522	2.516	2.553	2.540	2.515	2.552
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	9.573	10.207	11.567	15.534	10.579	8.996
				90°	9.645	9.515	11.505	11.529	9.993	8.506
			0.50 Hz	0°	9.067	10.915	14.038	12.666	9.149	9.324
				90°	8.641	10.476	12.291	13.949	9.167	12.474
			1 Hz	0°	10.484	10.896	11.712	10.949	10.919	9.868
				90°	9.965	11.434	12.209	11.628	9.011	9.326
			Average		9.558	10.574	12.239	12.709	9.803	9.749
	Total		0.33 Hz	0°	5.594	6.155	6.367	6.392	5.615	4.828
				90°	5.465	6.300	6.719	6.505	5.501	5.165
			0.50 Hz	0°	5.695	6.096	7.050	6.567	5.659	5.024
				90°	5.242	6.174	6.552	6.996	5.577	6.027
			1 Hz	0°	5.981	5.897	7.094	6.732	5.783	5.407
				90°	5.409	6.405	6.288	7.387	5.569	5.763
			Average		5.564	6.172	6.678	6.763	5.614	5.369

Unit: $\times 10^5$ psi

Results of ANOVA

```
Source    DF    Anova SS       Mean Square    F Value    Pr > F
----------------------------------------------------------------
ASPHALT   5     1.08266E+11    2.16531E+10    24.72      0.0001
CYCLE     2     4.22434E+09    2.11217E+09     2.41      0.1088
DEGREE    1     4.59852E+08    4.59852E+08     0.52      0.4750
----------------------------------------------------------------
R-Square = 0.827

Duncan              Mean       N   CYCLE
Grouping
         A          614295     12  1
         A
B        A          605508     12  0.5
B
B                   588216     12  0.33

Note: Means with the same letter are not significantly different
      (Alpha= 0.05)
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Table D-2 — Continued

SBBS modified AC-20 @ 5°C (41°F)

					No aging		PD oven 90 Days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.626	2.606	2.550	2.811	2.520	2.538
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	13.497	14.403	14.003	16.866	14.814	14.105
				90°	13.161	13.736	13.614	15.716	13.704	12.310
			0.50 Hz	0°	12.953	14.397	14.495	15.913	15.501	13.451
				90°	12.742	13.788	14.705	15.334	14.023	12.162
			1 Hz	0°	12.759	14.371	13.235	16.644	14.151	13.529
				90°	12.051	13.906	13.252	14.103	13.744	11.882
			Average		*12.861*	*14.114*	*13.884*	*15.596*	*14.323*	*12.903*
	Total		0.33 Hz	0°	10.139	10.592	10.898	12.086	11.524	10.541
				90°	9.989	10.228	10.443	12.321	10.421	9.359
			0.50 Hz	0°	9.745	10.795	10.822	12.357	11.031	10.285
				90°	10.196	10.348	10.531	12.318	10.748	9.594
			1 Hz	0°	10.440	11.032	10.734	12.767	11.635	10.370
				90°	10.086	10.913	10.256	11.763	10.339	9.750
			Average		*10.083*	*10.652*	*10.615*	*12.268*	*10.866*	*9.984*

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.02676E+11	4.05353E+10	46.58	0.0001
CYCLE	2	1.71955E+09	8.59774E+08	0.99	0.3854
DEGREE	1	2.15341E+10	2.15341E+10	24.74	0.0001

R-Square = 0.906

Duncan Grouping	Mean	N	DEGREE
A	1098924	18	0
B	1050009	18	90

NOTE: Means with the same letter are not significantly different (Alpha= 0.05)

Table D.2 — Continued

SEBS modified AC-20 @ 25°C (77°F)

					No aging		PD oven 90 days		Roof 6 months	
			Spec #		03	04	07	09	11	12
			Weight (in.)		2.519	2.488	2.515	2.550	2.616	2.547
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	10.220	9.741	12.465	11.883	8.739	8.403
				90°	9.426	10.806	11.852	12.745	8.964	8.114
			0.50 Hz	0°	9.133	11.754	12.029	14.074	9.690	7.879
				90°	8.731	10.291	10.589	10.793	9.692	8.308
			1 Hz	0°	9.300	9.856	12.223	9.750	11.363	7.848
				90°	9.962	9.995	10.978	12.033	10.819	7.011
			Average		9.662	10.407	11.489	11.879	9.744	7.927
	Total		0.33 Hz	0°	5.172	5.108	6.769	6.969	5.308	4.159
				90°	5.147	5.791	7.039	7.241	5.279	4.226
			0.50 Hz	0°	5.132	5.887	7.457	7.681	6.111	4.252
				90°	5.013	5.939	6.674	6.656	5.972	4.518
			1 Hz	0°	5.334	5.544	9.909	6.802	5.472	4.399
				90°	5.554	6.099	7.128	7.379	5.703	4.648
			Average		5.229	5.728	8.929	7.850	5.424	4.382

Unit: x10^3 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	3.24193E+11	6.48385E+10	95.74	0.0001
CYCLE	2	2.45716E+09	1.22858E+09	1.81	0.1823
DEGREE	1	2.58659E+09	2.58659E+09	3.82	0.0611

R-Square = 0.947

Table 6-2 -- Continued

SBS modified AC-5 @ 5°C (41°F)

					No aging		FD oven 30 days		Roof 6 months	
			Spec #		01	02	05	06	09	10
			Height (in.)		2.505	2.503	2.542	2.526	2.533	2.526
Resilient Modulus	Instantaneous	Cycle frequency	0.33 Hz	0°	12.049	11.410	13.557	13.626	12.267	12.488
				90°	12.572	11.308	14.216	13.801	12.538	12.755
			0.50 Hz	0°	12.128	11.405	13.759	14.305	12.949	12.223
				90°	12.598	10.861	13.479	13.922	12.215	12.417
			1 Hz	0°	12.382	11.525	13.485	13.604	12.497	11.515
				90°	12.199	11.178	13.333	13.525	11.935	11.565
			Average		*12.321*	*11.281*	*13.764*	*13.814*	*12.350*	*12.774*
	Total		0.33 Hz	0°	9.413	8.837	10.461	10.419	9.201	8.663
				90°	9.055	8.085	11.146	10.695	8.818	9.210
			0.50 Hz	0°	8.993	8.682	10.859	10.615	9.062	9.262
				90°	9.005	8.026	10.564	10.185	8.510	9.059
			1 Hz	0°	9.264	8.533	11.274	10.980	9.007	9.149
				90°	9.087	8.397	10.777	10.456	8.662	9.048
			Average		*9.123*	*8.492*	*10.847*	*10.559*	*8.878*	*9.056*

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	2.80908E+11	5.61816E+10	85.51	0.0001
CYCLE	2	1.77846E+09	8.89230E+08	1.35	0.2753
DEGREE	1	5.03442E+09	5.03442E+09	7.66	0.0101

R-Square = 0.942

Duncan Grouping	Mean	N	Degree
A	961062	18	0
B	937411	18	90

Note: Means with the same letter are not significantly different (Alpha= 0.05)

Table 8.2 — Continued

SEBS modified AC-5 @ 25°C (77°F)

				No aging		FD over 90 days		Roof 6 months	
		Spec #		03	04	07	08	11	12
		Height (in.)		2.506	2.534	2.535	2.490	2.541	2.532
Resilient Modulus	Instantaneous	Cycle frequency 0.33 Hz	0°	7.808	6.048	10.664	12.400	8.728	9.601
			90°	8.089	7.213	9.887	10.092	8.383	8.668
		0.50 Hz	0°	6.448	7.203	9.565	9.798	9.449	9.088
			90°	7.491	6.264	10.416	11.889	9.413	9.924
		1 Hz	0°	8.110	6.615	10.708	11.399	9.068	8.858
			90°	7.359	6.274	12.675	10.440	7.408	8.275
		Average		7.569	6.603	10.636	11.094	8.742	9.060
	Total	0.33 Hz	0°	3.908	3.523	6.871	6.664	4.257	4.793
			90°	3.704	3.733	6.615	6.166	4.004	4.502
		0.50 Hz	0°	3.555	3.851	6.231	6.323	4.411	4.610
			90°	3.694	3.675	6.941	6.454	4.217	4.694
		1 Hz	0°	3.938	3.717	6.225	5.661	4.655	4.872
			90°	3.628	3.703	6.737	6.170	4.169	4.651
		Average		3.755	3.703	6.603	6.609	6.287	6.703

Unit: x10^5 psi

Results of ANOVA

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ASPHALT	5	5.004228E+11	1.000084E+11	241.85	0.0001
CYCLE	2	6.209428E+07	3.104713E+07	0.08	0.9279
DEGREE	1	7.188218E+08	7.186218E+08	1.74	0.1986

R-Square = 0.978

Table D.3 Indirect tensile strength and fracture energy of dense-graded asphalt mixtures

Unmodified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.516	0.0474	471.33	905.37
	02	2.533	0.0744	476.27	1387.49
		Avg.	*0.0609*	*473.80*	*1096.43*
FD Oven 90 Days	05	2.554	0.0406	400.57	647.85
	06	2.537	0.0440	460.90	620.57
		Avg.	*0.0423*	*430.74*	*734.21*
Roof 6 Months	09	2.541	0.0846	435.56	1454.06
	10	2.544	0.0744	424.91	1195.31
		Avg	*0.0795*	*430.24*	*1324.69*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.536	0.3206	163.47	2194.29
	04	2.525	0.2644	155.81	1642.73
		Avg.	*0.2926*	*159.65*	*1918.51*
FD Oven 90 Days	07	2.539	0.1745	264.44	1643.20
	06	2.543	0.2053	257.66	2161.73
		Avg.	*0.1899*	*261.05*	*2002.47*
Roof 6 Months	11	2.550	0.3209	161.03	2099.42
	12	2.554	0.3080	165.64	2016.47
		Avg.	*0.3144*	*163.34*	*2057.95*

Table D.3 -- Continued

Gilsonite modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.529	0.0646	469.03	1552.43
	02	2.526	0.0609	457.20	1196.00
		Avg.	*0.0729*	*463.12*	*1375.42*
FD Oven 90 Days	05	2.541	0.0336	419.97	560.66
	06	2.521	0.0406	459.65	749.61
		Avg.	*0.0541*	*439.31*	*655.14*
Roof 6 Months	09	2.519	0.0912	477.62	1461.97
	10	2.543	0.0446	447.01	1497.26
		Avg.	*0.0829*	*462.32*	*1489.62*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.521	0.2335	245.59	2280.57
	04	2.552	0.2567	234.21	2410.56
		Avg.	*0.2451*	*239.90*	*2345.57*
FD Oven 90 Days	07	2.536	0.1796	339.56	2356.04
	08	2.541	0.1745	336.69	2349.12
		Avg.	*0.1771*	338.14	*2352.57*
Roof 6 Months	11	2.556	0.3060	232.94	2632.73
	12	2.539	0.2053	254.61	2093.39
		Avg.	*0.2567*	*243.93*	*2459.06*

Table D.3 -- Continued

Carbon black modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.533	0.0677	471.30	1260.18
	02	2.531	0.0812	476.74	1511.52
		Avg.	*0.0745*	*474.02*	*1385.85*
FD Oven 90 Days	05	2.543	0.0880	458.22	1507.95
	06	2.520	0.0440	399.45	704.93
		Avg.	*0.0660*	*428.84*	*1106.44*
Roof 6 Months	09	2.517	0.1015	475.05	1860.15
	10	2.538	0.0812	458.89	1491.68
		Avg.	*0.09135*	*466.97*	*1675.92*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.535	0.2567	201.77	2027.85
	04	2.550	0.3850	193.61	2912.20
		Avg.	*0.3209*	*197.69*	*2470.03*
FD Oven 90 Days	07	2.537	0.2053	250.60	2047.68
	08	2.539	0.1796	302.86	2124.22
		Avg.	*0.1925*	*276.73*	*2085.95*
Roof 6 Months	11	2.559	0.2310	215.50	1990.76
	12	2.540	0.2361	206.14	1914.57
		Avg	*0.2336*	*210.82*	*1952.67*

Table D.3 -- Continued

GTR-80 modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.548	0.0982	434.75	1674.65
	02	2.540	0.0880	447.17	1598.92
		Avg.	*0.0931*	*440.96*	*1636.79*
FD Oven 90 Days	05	2.593	0.0914	413.19	1416.42
	06	2.582	0.0643	410.16	1049.29
		Avg.	*0.0779*	*411.68*	*1232.86*
Roof 6 Months	09	2.612	0.1523	345.33	2067.90
	10	2.576	0.1456	370.88	2000.25
		Avg.	*0.1490*	*358.11*	*2034.08*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.567	0.3593	160.60	2233.18
	04	2.594	0.3337	160.01	2060.01
		Avg.	*0.3465*	*160.31*	*2146.60*
FD Oven 90 Days	07	2.576	0.2053	238.68	2051.64
	08	2.598	0.2053	238.68	2051.64
		Avg.	*0.2053*	*245.17*	*2041.55*
Roof 6 Months	11	2.525	0.2694	153.93	1713.20
	12	2.555	0.3593	152.43	2082.93
		Avg.	*0.3144*	*153.18*	*1898.07*

Table D.3 -- Continued

SBR modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.548	0.0880	435.07	1483.75
	02	2.547	0.1320	416.71	2129.67
		Avg.	*0.110*	***425.89***	*1806.71*
FD Oven 90 Days	05	2.554	0.0744	461.63	1369.44
	06	2.567	0.0592	498.76	1140.12
		Avg.	*0.0668*	***480.19***	***1254.78***
Roof 6 Months	09	2.545	0.1083	425.07	1793.84
	10	2.561	0.0914	441.99	1552.78
		Avg.	*0.0999*	***433.53***	***1673.31***

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.557	0.2823	165.90	1821.10
	04	2.553	0.2567	163.50	1644.34
		Avg.	*0.2695*	***164.7***	***1712.72***
FD Oven 90 Days	07	2.536	0.1796	273.30	2010.97
	08	2.568	0.1617	268.42	1659.91
		Avg.	*0.1707*	***278.86***	***1835.44***
Roof 6 Months	11	2.569	0.2618	205.04	2032.64
	12	2.580	0.2567	187.79	1915.18
		Avg.	*0.2593*	***196.42***	***1973.91***

Table D.3 -- Continued

EVA modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.523	0.0609	502.84	1147.00
	02	2.535	0.0575	526.47	1230.47
		Avg.	*0.0592*	*514.66*	*1188.74*
FD Oven 90 Days	05	2.533	0.0457	534.68	973.89
	06	2.524	0.0440	549.01	943.11
		Avg	*0.0449*	*541.85*	*958.50*
Roof 6 Months	09	2.571	0.0744	493.45	1373.86
	10	2.561	0.0948	519.94	1979.10
		Avg	*0.0846*	*506.70*	*1676.48*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.530	0.2181	248.11	2115.70
	04	2.534	0.2104	246.97	2038.92
		Avg.	*0.2143*	*247.54*	*2077.31*
FD Oven 90 Days	07	2.535	0.1283	380.82	1978.81
	08	2.543	0.1155	384.95	1769.34
		Avg	*0.1219*	*382.89*	*1874.08*
Roof 6 Months	11	2.577	0.2310	245.38	2199.43
	12	2.563	0.2053	238.51	1935.05
		Avg.	*0.2182*	*241.95*	*2067.24*

Table D.3 -- Continued

SEBS modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.548	0.0677	502.44	1285.29
	02	2.536	0.0575	478.54	1058.93
		Avg.	*0.0626*	*490.49*	*1172.11*
FD Oven 90 Days	05	2.550	0.0507	473.38	913.49
	06	2.566	0.0372	474.46	683.99
		Avg.	*0.0440*	*473.92*	*798.74*
Roof 6 Months	09	2.562	0.0609	479.09	1115.06
	10	2.561	0.0609	408.98	958.77
		Avg.	*0.0609*	*444.07*	*1036.92*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.589	0.1925	266.33	2005.66
	04	2.589	0.2053	253.24	2121.88
		Avg.	*0.1989*	*259.79*	*2063.77*
FD Oven 90 Days	07	2.560	0.1591	320.49	1910.20
	08	2.545	0.1488	347.41	2017.70
		Avg.	*0.1540*	*333.95*	*1963.95*
Roof 6 Months	11	2.526	0.2053	252.08	2230.69
	12	2.553	0.2053	264.34	2181.72
		Avg.	*0.2053*	*258.21*	*2206.21*

Table D.3 -- Continued

EVA modified AC-20

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.556	0.0677	475.06	1230.68
	02	2.541	0.0846	521.87	1804.79
		Avg.	*0.0762*	*498.47*	*1517.74*
FD Oven 90 Days	05	2.551	0.0507	488.98	938.58
	06	2.578	0.0744	419.44	1169.94
		Avg.	*0.0626*	*454.21*	*1054.26*
Roof 6 Months	09	2.571	0.0744	453.23	1365.57
	10	2.551	0.0778	493.36	1516.71
		Avg.	*0.0761*	*473.30*	*1441.14*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.567	0.2310	196.49	1694.02
	04	2.560	0.2284	203.92	1767.82
		Avg.	*0.2297*	*200.21*	*1730.92*
FD Oven 90 Days	07	2.567	0.1411	300.62	1624.40
	08	2.567	0.1155	305.40	1340.12
		Avg.	*0.1283*	*303.01*	*1482.26*
Roof 6 Months	11	2.550	0.2156	203.40	1742.69
	12	2.530	0.2310	210.16	1981.65
		Avg.	*0.2233*	*206.78*	*1862.17*

Table D.3 -- Continued

SEBS modified AC-20

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.568	0.1422	482.17	2561.39
	02	2.561	0.0626	431.31	1027.30
		Avg.	*0.1024*	*456.74*	*1794.35*
FD Oven 90 Days	05	2.569	0.0406	460.94	733.93
	06	2.562	0.0507	466.69	927.49
		Avg.	*0.0457*	*463.82*	*830.71*
Roof 6 Months	09	2.572	0.0711	456.09	1280.66
	10	2.551	0.1083	427.62	1761.49
		Avg.	*0.0897*	*441.86*	*1521.08*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.551	0.2515	219.47	2251.92
	04	2.552	0.2310	207.94	1970.16
		Avg	*0.2413*	*213.71*	*2111.04*
FD Oven 90 Days	07	2.531	0.1411	322.21	1800.20
	08	2.575	0.1411	325.46	1771.56
		Avg.	*0.1411*	*323.91*	*1785.88*
Roof 6 Months	11	2.564	0.2438	201.76	1867.30
	12	2.551	0.2438	211.05	2065.78
		Avg	*0.2438*	*206.41*	*1966.50*

Table D 3 -- Continued

EVA modified AC-5

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.532	0.1727	444.22	3125.28
	02	2.533	0.1727	464.72	3192.53
		Avg.	*0.1727*	*454.47*	*3159.91*
FD Oven 90 Days	05	2.543	0.0575	451.62	1051.76
	08	2.543	0.0778	463.01	1402.07
		Avg.	*0.0677*	*457.31*	*1226.92*
Roof 8 Months	09	2.552	0.1727	439.67	2971.06
	10	2.558	0.1828	443.15	3089.79
		Avg.	*0.1778*	*441.41*	*3030.43*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.535	0.2310	152.47	1382.71
	04	2.538	0.2053	150.08	1201.26
		Avg.	*0.2182*	*151.28*	*1291.99*
FD Oven 90 Days	07	2.546	0.1026	220.60	908.01
	08	2.545	0.1283	218.78	1125.04
		Avg.	*0.1155*	*219.69*	*1018.53*
Roof 6 Months	11	2.543	0.2695	160.85	1719.55
	12	2.544	0.2320	153.92	1403.40
		Avg.	*0.2593*	*157.39*	*1561.48*

Table D.3 -- Continued

SEBS modified AC-5

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.530	0.1456	428.04	2370.68
	02	2.548	0.1727	389.16	2642.72
		Avg.	***0.1592***	***408.6***	***2506.70***
FD Oven 80 Days	05	2.550	0.1134	404.85	1794.26
	06	2.565	0.0846	368.60	1189.78
		Avg.	***0.0990***	***386.73***	***1492.02***
Roof 6 Months	09	2.545	0.2065	372.66	2930.65
	10	2.558	0.1032	423.77	1780.97
		Avg.	***0.1549***	***398.22***	***2355.81***

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.556	0.2567	138.67	1317.13
	04	2.549	0.2567	145.16	1400.94
		Avg.	***0.2567***	***141.92***	***1359.04***
FD Oven 80 Days	07	2.550	0.1411	215.47	1194.30
	08	2.556	0.1411	186.68	1040.25
		Avg.	***0.1411***	***201.08***	***1117.28***
Roof 6 Months	11	2.554	0.2823	139.93	1571.24
	12	2.511	0.2823	144.82	1626.05
		Avg.	***0.2823***	***142.38***	***1598.65***

Table D.4 Indirect tensile strength and fracture energy of open-graded asphalt mixtures

Unmodified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.453	0.0711	327.91	919.13
	02	2.534	0.0845	259.43	849.03
		Avg.	*0.0778*	*293.67*	*884.08*
FD Oven 90 Days	05	2.708	0.1760	175.01	1150.41
	06	2.533	0.0677	298.70	732.01
		Avg.	*0.1219*	*236.86*	*941.21*
Roof 6 Months	09	2.538	0.0609	290.01	705.52
	10	2.546	0.0847	263.35	866.35
		Avg.	*0.0728*	*276.68*	*785.94*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.558	0.1592	126.27	811.85
	04	2.555	0.1593	119.79	740.54
		Avg.	*0.1593*	*123.03*	*776.20*
FD Oven 90 Days	07	2.515	0.0976	186.73	683.54
	08	2.537	0.1027	178.89	715.21
		Avg.	*0.1002*	*182.81*	*699.38*
Roof 6 Months	11	2.504	0.1885	145.91	941.92
	12	2.535	0.1540	137.85	837.17
		Avg.	*0.1803*	*141.88*	*889.55*

Table D-4 -- Continued

Gilsonite modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.476	0.0559	301.27	660.47
	02	2.461	0.0932	305.33	1076.66
		Avg.	*0.0746*	*303.30*	*666.56*
FD Oven 90 Days	05	2.505	0.0559	306.97	666.36
	06	2.520	0.0474	266.06	541.65
		Avg.	*0.0517*	*297.52*	*665.62*
Roof 6 Months	09	2.539	0.0746	307.07	671.13
	10	2.527	0.0745	276.37	606.96
		Avg.	*0.0746*	*292.72*	*639.66*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.496	0.1076	155.63	649.59
	04	2.501	0.1412	165.10	922.55
		Avg.	*0.1245*	*160.37*	*766.07*
FD Oven 90 Days	07	2.494	0.0699	235.03	792.66
	06	2.526	0.0976	216.62	631.43
		Avg.	*0.0936*	*226.63*	*612.15*
Roof 6 Months	11	2.532	0.1335	164.01	649.09
	12	2.507	0.1156	167.59	770.72
		Avg.	*0.1246*	*165.60*	*609.91*

Table D.4 -- Continued

Carbon black modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.552	0.0576	278.06	634.74
	02	2.522	0.0614	261.62	890.36
		Avg.	*0.0695*	*279.85*	*762.56*
FD Oven 90 Days	05	2.522	0.0610	296.37	687.62
	06	2.531	0.0610	295.74	712.42
		Avg.	*0.0610*	*296.66*	*706.62*
Roof 6 Months	09	2.525	0.0677	307.49	805.36
	10	2.527	0.0745	307.00	661.39
		Avg.	*0.0711*	*307.25*	*843.38*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.522	0.1798	141.58	1006.59
	04	2.512	0.1926	140.47	1049.56
		Avg.	*0.1862*	*141.03*	*1028.08*
FD Oven 90 Days	07	2.537	0.1265	199.51	959.23
	08	2.534	0.1079	193.25	828.07
		Avg.	*0.1182*	*196.36*	*693.65*
Roof 6 Months	11	2.525	0.1284	145.63	750.26
	12	2.523	0.1928	141.12	1042.54
		Avg.	*0.1606*	*145.36*	*896.41*

Table D.4 -- Continued

GTR-80 modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.437	0.0812	313.01	992.79
	02	2.355	0.0777	362.65	1084.29
		Avg.	*0.0795*	*337.83*	*1038.54*
FD Oven 90 Days	05	2.455	0.0609	309.07	715.74
	06	2.458	0.0576	311.08	707.18
		Avg.	*0.0593*	*310.08*	*711.46*
Roof 6 Months	09	2.478	0.0881	318.50	1062.43
	10	2.460	0.0882	307.91	1046.18
		Avg.	*0.0882*	*313.21*	*1054.31*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.436	0.1540	151.07	872.00
	04	2.464	0.1539	149.91	865.82
		Avg.	*0.1540*	*150.49*	*868.91*
FD Oven 90 Days	07	2.456	0.1029	197.18	796.24
	08	2.464	0.0897	193.07	677.50
		Avg.	*0.0963*	*195.13*	*736.87*
Roof 6 Months	11	2.465	0.1154	145.68	659.67
	12	2.474	0.1287	156.28	783.17
		Avg.	*0.1221*	*150.98*	*721.42*

Table D.4 -- Continued

SBR modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.457	0.0981	278.11	1061.23
	02	2.469	0.0615	280.72	1021.10
		Avg.	*0.0946*	*279.41*	*1041.17*
FD Oven 60 Days	05	2.462	0.0576	314.60	702.17
	06	2.457	0.0576	267.44	660.24
		Avg.	*0.0576*	*366.17*	*661.21*
Roof 6 Months	09	2.499	0.0779	275.70	857.61
	10	2.472	0.0644	305.66	785.39
		Avg.	*0.0712*	*266.68*	*822.65*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.484	0.1795	120.95	672.29
	04	2.441	0.1798	143.41	966.91
		Avg.	*0.1797*	*132.18*	*919.80*
FD Oven 90 Days	07	2.502	0.0770	182.25	564.20
	08	2.534	0.1028	179.46	708.39
		Avg.	*0.0699*	*260.87*	*636.30*
Roof 6 Months	11	2.466	0.1540	134.76	814.42
	12	2.515	0.1542	131.60	764.80
		Avg.	*0.1541*	*133.26*	*789.61*

Table D.4 -- Continued

EVA modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.477	0.0695	342.64	937.45
	02	2.474	0.0847	325.92	1046.85
		Avg.	*0.0771*	*334.28*	*992.15*
FD Oven 90 Days	05	2.475	0.0542	332.57	725.78
	06	2.479	0.0474	313.99	584.65
		Avg	*0.0508*	*323.28*	*655.22*
Roof 6 Months	09	2.507	0.0678	295.71	767.69
	10	2.527	0.0863	300.92	1006.42
		Avg.	*0.0771*	*298.32*	*887.06*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.431	0.1336	172.27	882.88
	04	2.509	0.1029	154.32	621.21
		Avg	*0.1183*	*163.30*	*752.05*
FD Oven 90 Days	07	2.501	0.0772	212.28	617.71
	08	2.501	0.0771	224.47	685.16
		Avg.	*0.0772*	*218.38*	*651.44*
Roof 6 Months	11	2.531	0.1158	159.69	732.55
	12	2.521	0.1156	163.97	755.31
		Avg.	*0.1157*	*161.83*	*743.93*

Table D.4 — Continued

SEBS modified AC-30

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.489	0.0915	296.99	1036.41
	02	2.526	0.0677	265.29	700.04
		Avg.	0.0796	281.14	828.23
FD Oven 90 Days	05	2.558	0.0440	291.71	493.21
	06	2.525	0.0780	230.58	676.99
		Avg.	0.0610	261.15	585.10
Roof 6 Months	09	2.519	0.2708	250.77	2548.67
	10	2.516	0.0710	268.63	747.19
		Avg.	0.1709	259.70	1647.93

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.522	0.1028	157.31	599.85
	04	2.516	0.1157	179.77	845.84
		Avg.	0.1093	168.54	722.85
FD Oven 90 Days	07	2.553	0.0771	201.41	605.22
	08	2.540	0.0771	221.94	640.21
		Avg.	0.0771	211.68	622.72
Roof 6 Months	11	2.515	0.1156	189.60	876.12
	12	2.552	0.1337	163.23	834.02
		Avg.	0.1247	176.42	855.87

Table D.4 -- Continued

EVA modified AC-20

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.500	0.0883	315.22	1058.65
	02	2.510	0.0833	308.94	1041.82
		Avg.	*0.0858*	*312.88*	*1050.24*
FD Oven 90 Days	05	2.514	0.0712	332.46	942.40
	06	2.520	0.0813	315.79	989.69
		Avg.	*0.0763*	*324.13*	*966.05*
Roof 6 Months	09	2.478	0.0693	316.88	877.26
	10	2.521	0.0883	323.73	1175.79
		Avg.	*0.0788*	*320.31*	*1026.53*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.509	0.1293	114.62	568.29
	04	2.537	0.1672	122.70	780.95
		Avg.	*0.1483*	*118.66*	*674.62*
FD Oven 90 Days	07	2.471	0.1029	207.89	796.89
	08	2.478	0.0641	172.82	441.67
		Avg.	*0.0835*	*190.36*	*619.28*
Roof 6 Months	11	2.478	0.1542	148.59	888.53
	12	2.490	0.1798	146.50	1034.68
		Avg.	*0.1670*	*147.55*	*961.61*

Table D.4 -- Continued

SEBS modified AC-20

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.525	0.0915	289.94	1022.71
	02	2.506	0.0643	259.53	678.30
		Avg.	***0.0779***	***274.74***	***850.51***
FD Oven 90 Days	05	2.550	0.0406	253.45	402.60
	06	2.511	0.0711	259.47	712.54
		Avg.	***0.0559***	***256.46***	***557.67***
Roof 6 Months	09	2.528	0.0576	277.51	631.07
	10	2.539	0.0660	255.57	660.39
		Avg.	***0.0618***	***266.54***	***655.73***

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.516	0.1336	139.29	699.61
	04	2.488	0.1157	153.21	666.08
		Avg.	***0.1247***	***146.25***	***662.65***
FD Oven 90 Days	07	2.515	0.0719	194.87	559.99
	06	2.550	0.0642	200.36	512.28
		Avg.	***0.0662***	***197.62***	***536.14***
Roof 6 Months	11	2.516	0.1078	146.67	643.35
	12	2.547	0.1541	125.04	752.33
		Avg.	***0.1318***	***135.86***	***697.84***

Table D.4 -- Continued

EVA modified AC-5

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.511	0.1393	253.56	1379.94
	02	2.481	0.1256	249.41	1235.65
		Avg.	*0.1325*	*251.49*	1307.88
FD Oven 90 Days	05	2.491	0.0814	265.39	856.94
	06	2.491	0.0796	289.21	923.94
		Avg.	*0.0805*	*277.30*	*890.44*
Roof 6 Months	09	2.496	0.0897	247.03	872.96
	10	2.502	0.0882	256.71	882.95
		Avg.	*0.0890*	*251.87*	*877.96*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.498	0.1286	88.03	427.40
	04	2.515	0.1543	92.56	558.86
		Avg.	0.1415	*90.30*	*493.13*
FD Oven 90 Days	07	2.446	0.0896	146.47	526.58
	08	2.480	0.0771	133.46	413.37
		Avg.	*0.0834*	139.97	*469.98*
Roof 6 Months	11	2.494	0.1157	111.74	488.29
	12	2.485	0.1543	116.62	683.47
		Avg.	*0.1350*	*114.18*	585.88

Table D.4 -- Continued

SEBS modified AC-5

41°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	01	2.506	0.0830	251.63	791.28
	02	2.503	0.0779	251.48	907.72
		Avg.	*0.0805*	*251.56*	*799.59*
FD Oven 90 Days	05	2.542	0.0372	249.67	369.97
	06	2.526	0.0423	253.92	426.98
		Avg.	*0.0398*	*251.80*	*397.98*
Roof 6 Months	09	2.533	0.0643	268.47	685.19
	10	2.526	0.0694	262.19	729.46
		Avg.	*0.0669*	*265.33*	*707.32*

77°F

	Spec#	Height (inch)	Corresponding ultimate Strain (%)	Stress (psi)	Energy (pascal)
No aging	03	2.547	0.1542	98.71	627.42
	04	2.534	0.1671	95.87	607.19
		Avg.	*0.1687*	*97.29*	*617.31*
FD Oven 90 Days	07	2.536	0.0770	155.71	466.72
	08	2.498	0.0667	158.62	416.60
		Avg.	*0.0719*	*157.17*	*441.66*
Roof 6 Months	11	2.541	0.1027	209.96	434.65
	12	2.532	0.1156	116.24	509.37
		Avg.	*0.1092*	*112.60*	*472.01*

APPENDIX E

RESULTS OF RHEOLOGICAL AND CHEMICAL TESTS ON RECOVERED RESIDUES

Table E Rheological and chemical properties of recovered asphalt blends

ABSOLUTE VISCOSITY @ 60°C

Dense-Graded

Unit: poise

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	9,798	42,761	12,441
AC-30+Gilsonite	22,475	129,510	31,617
AC-30+GTR-80	13,615	30,880	9,032
AC-30+SBR	8,323	332,538	12,096
AC-30+EVA	22,089	196,328	22,824
AC-30+SEBS	13,458	80,199	21,016
AC-20+EVA	52,907	157,613	53,790
AC-20+SEBS	10,191	69,346	11,130
AC-5+EVA	6,490	130,676	7,520
AC-5+SEBS	52,404	343,577	71,841

Open-Graded

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	9,343	29,363	13,257
AC-30+Gilsonite	26,745	77,928	33,523
AC-30+GTR-80	11,627	40,438	19,236
AC-30+SBR	20,783	61,646	28,774
AC-30+EVA	55,301	123,942	70,326
AC-30+SEBS	63,390	114,855	85,574
AC-20+EVA	9,576	35,966	17,087
AC-20+SEBS	81,763	133,639	81,654
AC-5+EVA	3,079	102,677	9,720
AC-5+SEBS	15,580	157,495	73,273

Table E --Continued

Penetration @ 25°C

Dense-Graded

Unit: 0.1 mm

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	35	18	32
AC-30+Gilsonite	21	13	19
AC-30+GTR-80	35	21	30
AC-30+SBR	33	16	33
AC-30+EVA	28	17	25
AC-30+SEBS	24	14	22
AC-20+EVA	32	17	28
AC-20+SEBS	24	13	23
AC-5+EVA	47	28	47
AC-5+SEBS	37	25	36

Open-Graded

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	30	17	25
AC-30+Gilsonite	19	13	18
AC-30+GTR-80	33	20	28
AC-30+SBR	31	22	28
AC-30+EVA	23	18	22
AC-30+SEBS	22	14	18
AC-20+EVA	31	19	25
AC-20+SEBS	25	15	21
AC-5+EVA	46	27	36
AC-5+SEBS	35	23	28

Table E --Continued

Constant power viscosity at 15°C (59°F)

Dense-Graded

Unit: x10^7 Pa s

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	4.14	10.10	15.00
AC-30+Gilsonite	12.00	43.00	11.00
AC-30+EVA	15.00	36.00	17.00
AC-30+SEBS	20.00	43.00	23.00
AC-20+EVA	8.12	9.76	16.00
AC-20+SEBS	26.00	48.00	15.00
AC-5+EVA	0.27	3.08	1.46
AC-5+SEBS	14.00	28.00	14.00

Open-Graded

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	9.70	210.00	45.00
AC-30+Gilsonite	50.00	85.00	18.00
AC-30+EVA	8.48	70.00	28.00
AC-30+SEBS	18.00	50.00	31.00
AC-20+EVA	6.35	15.00	9.01
AC-20+SEBS	19.00	31.00	22.00
AC-5+EVA	0.64	6.83	1.81
AC-5+SEBS	3.43	15.00	5.99

Table E --Continued

Constant power viscosity at 25°C (77°F)

Dense-Graded

Unit. x10^5 Pa s

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	6.20	51.60	10.90
AC-30+Gilsonite	23.00	58.00	46.90
AC-30+EVA	49.30	21.20	95.60
AC-30+SEBS	96.50	246.00	163.00
AC-20+EVA	14.60	172.00	21.30
AC-20+SEBS	79.50	389.00	205.00
AC-5+EVA	6.88	40.40	9.12
AC-5+SEBS	53.70	268.00	105.00

Open-Graded

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	2.38	1700.00	16.20
AC-30+Gilsonite	23.30	315.00	26.70
AC-30+EVA	138.00	260.00	75.20
AC-30+SEBS	176.00	304.00	222.00
AC-20+EVA	42.00	512.00	74.90
AC-20+SEBS	139.00	240.00	251.00
AC-5+EVA	8.05	78.30	33.10
AC-5+SEBS	27.20	196.00	168.00

Table E --Continued

Carbonyl Ratio

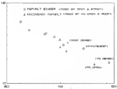
Dense-Graded

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	0.4930904	0.6469975	0.5191419
AC-30+Gilsonite	0.5315714	0.7402547	0.5541570
AC-30+EVA	0.5773697	0.7847956	0.5887335
AC-30+SEBS	0.4999251	0.6970290	0.5194652
AC-20+EVA	0.5560885	0.7499294	0.5882561
AC-20+SEBS	0.5016046	0.7229029	0.5225433
AC-5+EVA	0.5855818	0.7988821	0.6027399
AC-5+SEBS	0.5294615	0.7370946	0.5361369

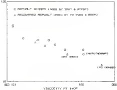
Open-Graded

ASPHALT	No Aging	FD 90 days	Roof 6 months
AC-30	0.5027259	0.6643684	0.5566492
AC-30+Gilsonite	0.5577318	0.6751874	0.5631493
AC-30+EVA	0.5485414	0.6865340	0.5675240
AC-30+SEBS	0.4939038	0.6499649	0.5103210
AC-20+EVA	0.5189752	0.7014247	0.5379254
AC-20+SEBS	0.4676343	0.6593960	0.4996310
AC-5+EVA	0.5385570	0.7243330	0.5543256
AC-5+SEBS	0.4844730	0.7159171	0.4913251

APPENDIX F
RELATIONSHIP BETWEEN PENETRATION AND VISCOSITY ON RECOVERED RESIDUES

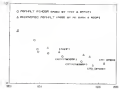


Conventional AC-30



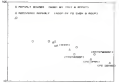
SBR Modified AC-30

Figure F.1 Pen-vis relationship of modified asphalt binder at different long-term aging conditions

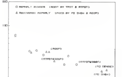


EVA Modified AC-30

Figure F.1 --Continued

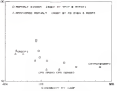


EVA Modified AC-20

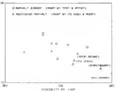


EVA Modified AC-5

Figure F.1 --Continued

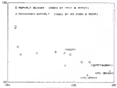


SEBS Modified AC-30



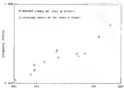
SEBS Modified AC-20

Figure F.1 --Continued

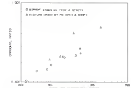


SBS Modified AC-5

Figure F.1 --Continued

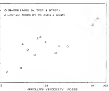


EVA modified AC-30

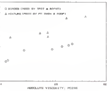


EVA modified AC-20

Figure F.2 Carbonyl ratio vs. viscosity relationship of different modified asphalts at different aging conditions



EVA modified AC-5



SEBS modified AC-5

Figure F.2 --Continued

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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